104

ADAPTIVE IMPEDANCE RELAY FOR THE PROTECTION OF SERIES COMPENSATED LINES

By

Lixuan Wu

A THESIS
Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Electrical and Computer Engineering
The University of Manitoba
Winnipeg, Manitoba, Canada

ADAPTIVE IMPEDANCE RELAY FOR THE PROTECTION OF SERIES COMPENSATED LINES

BY

LIXUAN WU

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ISBN 0-612-13579-9

Name ______________________________

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

Electronic and Electrical | 0 6 0 7 | U·M·I

SUBJECT TERM | SUBJECT CODE

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS
Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION
General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0998
Physical 0523
Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0340
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS
Language
- General 0679
- Ancient 0289
- Linguistics 0290
- Modern 0291

Literature
- General 0401
- Classical 0294
- Comparative 0295
- Medieval 0297
- Modern 0298
- African 0316
- American 0591
- Asian 0305
- Canadian (English) 0352
- Canadian (French) 0355
- English 0593
- Germanic 0311
- Latin American 0312
- Middle Eastern 0315
- Romance 0313
- Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY
Philosophy 0422
Religion
- General 0318
- Biblical Studies 0321
- Clergy 0319
- History of 0320
- Philosophy of 0322

Theology 0469

SOCIAL SCIENCES
American Studies 0323
Anthropology
- Archaeology 0324
- Cultural 0326
- Physical 0327

Business Administration
- General 0310
- Accounting 0272
- Banking 0770
- Management 0454
- Marketing 0338

Canadian Studies 0385
Economics
- General 0501
- Agricultural 0503
- Commerce-Business 0505
- Finance 0508
- History 0509
- Labor 0510
- Theory 0511

Folklore 0358
Geography 0366
Gerontology 0351
History
- General 0578
- Ancient 0579
- Medieval 0581
- Modern 0582
- Black 0328
- African 0331
- Asia, Australia and Oceania 0332
- Canadian 0334
- European 0335
- Latin American 0336
- Middle Eastern 0333
- United States 0337

History of Science 0585
Law 0398
Political Science
- General 0615
- International Law and Relations 0616
- Public Administration 0617

Recreation 0814
Social Work 0452
Sociology
- General 0626
- Criminology and Penology 0627
- Demography 0938
- Ethnic and Racial Studies 0631
- Individual and Family Studies 0628
- Industrial and Labor Relations 0629
- Public and Social Welfare 0630
- Social Structure and Development 0700
- Theory and Methods 0344

Transportation 0709
Urban and Regional Planning 0999
Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES
Agriculture
- General 0473
- Agronomy 0285
- Animal Culture and Nutrition 0475
- Animal Pathology 0476
- Food Science and Technology 0359
- Forestry and Wildlife 0478
- Plant Culture 0479
- Plant Pathology 0480
- Plant Physiology 0817
- Range Management 0777
- Wood Technology 0746

Biology
- General 0306
- Anatomy 0287
- Biostatistics 0308
- Botany 0309
- Cell 0379
- Ecology 0329
- Entomology 0353
- Genetics 0369
- Limnology 0793
- Microbiology 0410
- Molecular 0307
- Neuroscience 0317
- Oceanography 0416
- Physiology 0433
- Radiation 0821
- Veterinary Science 0778
- Zoology 0472

Biophysics
- General 0786
- Medical 0760

EARTH SCIENCES
Biogeochemistry 0425
Geochemistry 0996
Geodesy 0370
Geology 0372
Geophysics 0373
Hydrology 0388
Mineralogy 0411
Paleobotany 0345
Paleoecology 0426
Paleontology 0418
Paleozoology 0985
Palynology 0427
Physical Geography 0368
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES
Environmental Sciences 0768
Health Sciences
- General 0566
- Audiology 0300
- Chemotherapy 0992
- Dentistry 0567
- Education 0350
- Hospital Management 0769
- Human Development 0758
- Immunology 0982
- Medicine and Surgery 0564
- Mental Health 0347
- Nursing 0569
- Nutrition 0570
- Obstetrics and Gynecology 0380
- Occupational Health and Therapy 0354
- Ophthalmology 0381
- Pathology 0571
- Pharmacology 0419
- Pharmacy 0572
- Physical Therapy 0382
- Public Health 0573
- Radiology 0574
- Recreation 0575
- Speech Pathology 0460
- Toxicology 0383

Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences

Chemistry
- General 0485
- Agricultural 0749
- Analytical 0486
- Biochemistry 0487
- Inorganic 0488
- Nuclear 0738
- Organic 0490
- Pharmaceutical 0491
- Physical 0494
- Polymer 0495
- Radiation 0754

Mathematics 0405
Physics
- General 0605
- Acoustics 0986
- Astronomy and Astrophysics 0606
- Atmospheric Science 0608
- Atomic 0748
- Electronics and Electricity 0607
- Elementary Particles and High Energy 0798
- Fluid and Plasma 0759
- Molecular 0609
- Nuclear 0610
- Optics 0752
- Radiation 0756
- Solid State 0611

Statistics 0463

Applied Sciences

Applied Mechanics 0346
Computer Science 0984
Engineering
- General 0537
- Aerospace 0538
- Agricultural 0539
- Automotive 0540
- Biomedical 0541
- Chemical 0542
- Civil 0543
- Electronics and Electrical 0544
- Heat and Thermodynamics 0348
- Hydraulic 0545
- Industrial 0546
- Marine 0547
- Materials Science 0794
- Mechanical 0548
- Metallurgy 0743
- Mining 0551
- Nuclear 0552
- Packaging 0549
- Petroleum 0765
- Sanitary and Municipal 0554
- System Science 0790

Geotechnology 0428
Operations Research 0796
Plastics Technology 0795
Textile Technology 0994

PSYCHOLOGY
General 0621
Behavioral 0384
Clinical 0622
Developmental 0620
Experimental 0623
Industrial 0624
Personality 0625
Physiological 0989
Psychobiology 0349
Psychometrics 0632
Social 0451

I hereby declare that I am the sole author of this thesis.

I authorize the University of Manitoba to lend this thesis to other institutions or individuals for the purpose of scholarly research.

LIXUAN WU

I further authorize the University of Manitoba to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

LIXUAN WU

ABSTRACT

Series capacitors provides a cost–efficient way to increase the transmission capacity per circuit of an existing transmission line. It also helps to increase the flexibilities in the load–flow distribution control and the stability levels of a power system. However, the series compensations of transmission lines are known to cause problems to the protection of these lines.

As the analysis in this thesis shows, series compensation mainly causes problems for non–pilot fast–relaying protection systems, such as an impedance type relay, but causes less problems for pilot protection systems. The severity of these problems caused by the series compensation for an impedance relay is determined by many factors: such as series capacitor's location (end–compensation or mid–compensation), relay PT location, series capacitor's protection circuit type. Some of these problems are easy to solve, which have been shown in the thesis. Among them, using impedance relays to protect a mid–compensated line is the most difficult one to solve.

An adaptive impedance relaying algorithm has been developed in this study to solve the protection of a mid–compensated line using impedance relays. In this thesis, a theoretical background of this adaptive algorithm was provided. The thesis also went on to analyze the feasibilities of this algorithm under different real situations. The simulation results of this study show that this adaptive algorithm can be used to solve the fast relaying problem of a mid–compensated line.

ACKNOWLEDGEMENT

I wish to express my sincere thanks and gratitude to my research supervisor, Professor Peter G. McLaren at Department of Electrical & Computer Engineering, University of Manitoba, for his guidance and encouragement throughout the course of this research work.

The financial support from Manitoba Hydro and additional funding from NSERC (CANADA) for this project is gratefully acknowledged. I also wish to express my appreciation to all professors, colleagues and technical staffs at the Power System Group, Department of Electrical & Computer Engineering, University of Manitoba, for their support, assistance and friendship during the course of this study, which make my years in Winnipeg a very pleasant experience.

Finally, I wish to express my greatest thanks to my husband and my family for their patience and sacrifice, as well as their continuous support and encouragement, for which the author is in deep debt.

LIXUAN WU

Table of Contents

List of Figures

FIGURE **PAGE**

List of Tables

TABLE **PAGE**

CHAPTER 1: INTRODUCTION

§ 1–1 The problem

Series compensation is widely used in long distance HV or EHV transmission systems to increase the transmission capacity per circuit. The capital investment of installing a series capacitor to increase the transmission capacity of a line is much lower than building up another transmission line for the same purpose. This is the major reason which favors series compensation. Series compensation also offers other advantages: a series compensated line has less environment impact than adding another line; it helps to increase the system steady–state stability as well as transient stability levels; it has more flexible operation modes which allow for a more flexible load flow distribution control when the series capacitors are installed in several banks.

However, series compensation is well known to cause problems for protection systems, especially fast relaying systems, on the compensated lines. The protection systems used for HV or EHV transmission systems basically can be divided into two groups: the pilot protection systems and the non–pilot protection systems. The pilot protection systems use various communication links to exchange fault information measured at both ends of a line. These systems mainly compare the fault directions detected at both ends of the line and their function is less affected by the series compensation. The non–pilot systems use only local fault information at the one end of a line, where the protection system is installed. A non–pilot system operates faster than a pilot protection system as its operation is not affected by the communication channel's delay. Among different non–pilot protection systems, the impedance relay is the one which has been most widely used in uncompensated transmission lines as it provides good selectivity, large coverage area and fast operating speed.

There are some problems when an impedance relay is used to protect a series compensated line. The main problem, which is caused by the series compensation, for an impedance relay is that the series capacitor changes the fault impedance seen by the relay. The series capacitor makes the line look "shorter" and the line impedance becomes "smaller" to the relay. To avoid the over–reach problem of the impedance relay, i.e. to avoid the false tripping of the relay on the faults at adjacent lines, a "smaller" relay setting ($Z_{setting}'$) has to be used for the conventional impedance relays (Fig. 1.1.1). As a result fast relaying coverage is lost for faults near the capacitor bank, unless communication is available. This is because zone1 relaying at both ends of the line do not overlap their coverage.

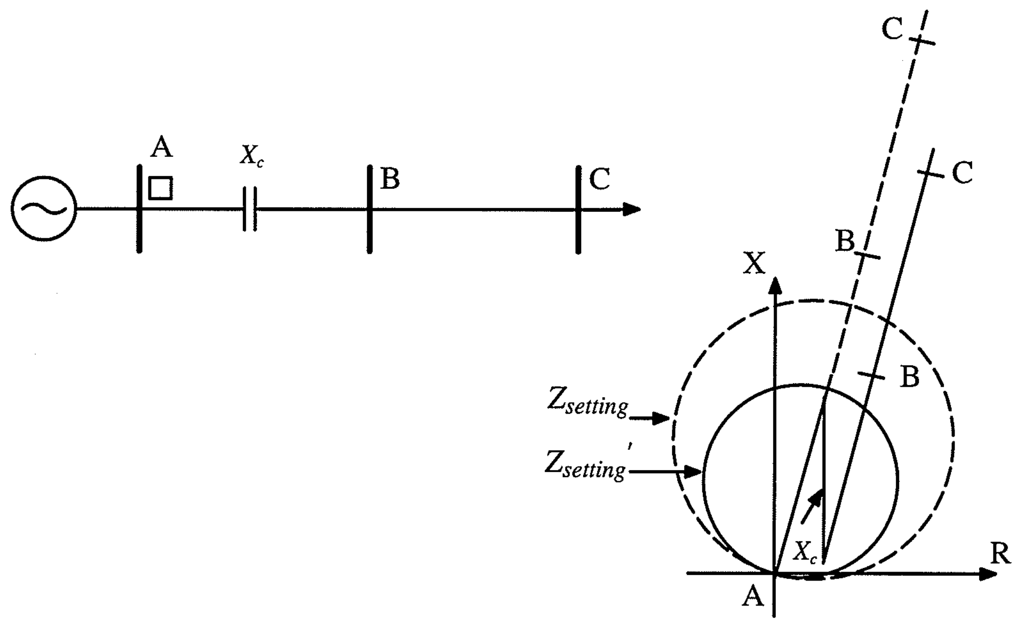


Fig. 1.1.1. The main problem of an impedance relay caused by the series compensation

In Fig. 1.1.1, the relay setting ($Z_{setting}$) is $0.85 \times Z_l$ for a non–compensated line and setting ($Z_{setting}'$) is $0.85 \times (Z_l - j\ X_c)$ for a compensated line.

The problem is further complicated by the in–service status of the series capacitor (i.e. the series capacitor can be either in–service or out–of–service, and may have several compensation degrees if separate capacitor banks are used) and the action of the series capacitor's protection circuit. The severity of the problem is also affected by the location of the series capacitor on the line, the location of the relay PT in relation to the series capacitor's location for an end–compensated line, and the types of protection circuits of the series capacitor. Due to the complexity of the problems caused by all these factors, a detailed discussion of these problems is omitted here, and will be presented in the later chapters.

This study comes from the need to provide a fast relaying system for a series compensated 500 kV transmission line between the Manitoba Hydro System and the Northern States Power System. The line consists of two line sections. The north line section is from the Dorsey converter station to the Forbes substation and the south line section is from Forbes to the Chisago substation. Series capacitors were installed in both line sections in 1993 to increase the transmission capacity of the line.

Both off–line studies [1] and on–site relay tests [10] were conducted prior to the installation of the series capacitor in this line. The results show that the settings of the existing relay systems of this line should be changed to prevent over–reach operation of the relays when the series capacitor is in–service. The results also show that these protection systems will have problems providing adequate fast relaying under certain operating conditions when the adjusted settings are used [10]. The most severe condition occurs when the series capacitor is out–of–service while the relay is using the capacitor in–service setting. Under this condition, part of the line will lose fast relaying coverage completely, which is provided by the zone 1 of the relays. The clearance of the faults in these regions will completely rely on the operation of the relay zone 2 with 0.5 sec. time delay or the actions of other pilot protection systems with some time delays.

§ 1–2 The goal of this study

The problems of protecting a series–compensated line have been studied previously. Many efforts were made to study different aspects of the problem. However, due to the complexity of the problem, so far no complete solution has been suggested or developed to solve the fast relaying problem for a series–compensated line. Furthermore, most of the previous studies have concentrated on one aspect of the problem, thus there is a lack of the complete clarification of the problem related to the fast relaying of a series compensated line.

This study has two goals. The first goal is to further clarify the problems associated with the fast relaying of a series–compensated line using a conventional impedance relay. The second goal is to develop an adaptive relay algorithm, which will provide adequate fast relaying for a series compensated line.

§ 1–3 Scope of the thesis

This thesis is divided into two major parts corresponding to its two goals. The first part is the analysis of the problems of an impedance relay caused by the series compensation. The second part is the theory and implementation of the adaptive digital MHO relaying algorithm developed in this study for fast relaying of a series compensated line.

The first part of the thesis consists of Chapter 2, 3 and 4. In Chapter 2, the need for series compensation, its advantages, the protection circuit required for the series capacitors, and the types of series capacitor protection circuits are presented, providing a necessary background for later analysis of the problems. Impedance relaying problems caused by series compensation are analyzed in detail in Chapter 3. Chapter 4 provides necessary information about the Dorsey–Forbes–Chisago line, as well as its modelling and simulation on the PSCAD/EMTDC Electromagnetic Transient software. The simulated system was used extensively in the development and the testing of the new adaptive relay algorithm.

Chapters 5 to 7 make up the second part of the thesis. The basic theory of the adaptive MHO relaying algorithm developed in this study is presented in Chapter 5. The feasibility of the algorithm under different fault conditions are analyzed and the modifications to the algorithm are discussed in Chapter 6 when these conditions are considered. Chapter 7 describes the implementation and the tests of the adaptive algorithm on the PSCAD/EMTDC. The considerations and steps to implement this algorithm on the APT relay platform (a common hardware and software platform for Manitoba Hydro relaying projects) is also briefly discussed in the Chapter 7.

Chapter 8, the last chapter, summarizes the main achievements of this study. The conclusions and the suggestions for further studies are also presented in this chapter.

CHAPTER 2: SERIES COMPENSATION

§ 2–1 Introduction

Due primarily to its economical advantages, series compensation has been widely used in the HV/EHV (High Voltage/Extra High Voltage) transmission systems of present–day power systems to increase the transmission capacity per circuit of a transmission system. Series compensation also has other advantages, such as increase in the system steady–state and transient stability level.

In this chapter, the purpose of HV/EHV long distance transmission, its problems, the advantages of using series compensation to solve these problems, the common types of series compensated lines, and the issues related to protecting a series capacitor are discussed to provide a necessary background for analysis in the later chapters.

§ 2–2 HV/EHV long distance AC power transmission

The purpose for building HV/EHV AC transmission lines arises primarily from the need to transmit bulk electric power from remote generating stations to the load center or to interconnect two main systems located far from each other.

In AC power transmission, the maximum power of a transmission line which can be transmitted continuously is determined mainly by the steady–state stability considerations. Fig. 2.2.1 shows a typical one–machine system connected to an infinite bus (main system). In Fig. 2.2.1, E_g is the EMF of the generator, E is the equivalent EMF of the infinite bus main system, and "X" is the total impedance between the E_g and E (which includes generator's impedance, transformer's impedance and transmission line's impedance). To simplify the analysis, the distributed parameter characteristics of the transmission line are treated as a lumped impedance with resistances and shunt capacitances neglected.

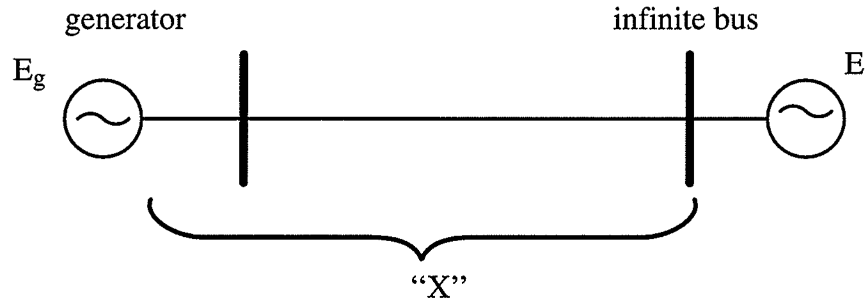


Fig. 2.2.1 Typical one–machine–to–infinite–bus system

For such a system, the active power "P" transferred verses the power angle δ (between E_g and E) has the following relationship:

$$P = \frac{E_g E}{X} \sin(\delta) \tag{2.2.1}$$

This relationship can be plotted in a P–δ diagram as shown in Fig. 2.2.2

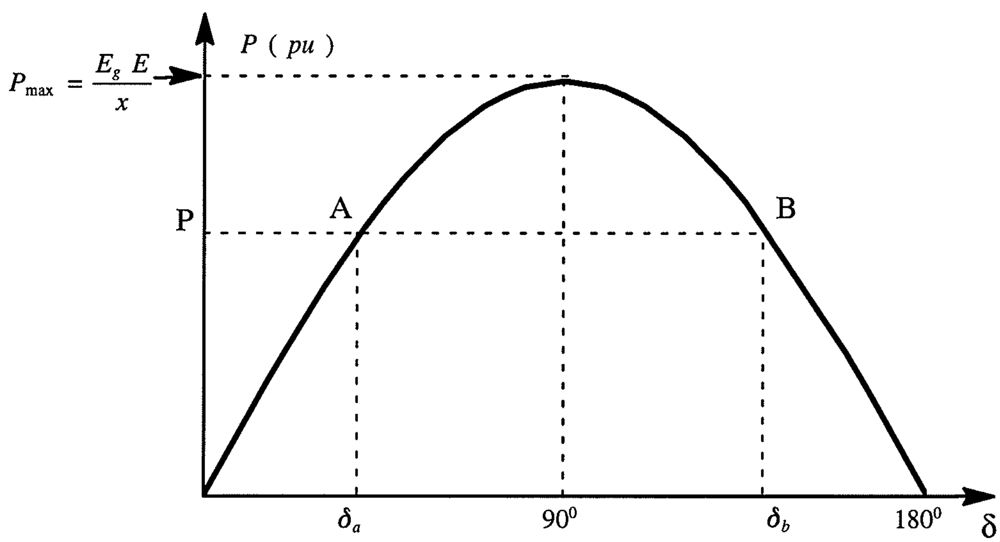


Fig. 2.2.2 P–δ plot of one–machine–to–infinite–bus system

According to the diagram, there are two possible operating points A (δ_a) and B (δ_b) for any P value less than P_{max} ($= E_gE$/"X"). The operating point A is stable while B is not. Any change at the operating point A will finally settle down at that point but point B will be unstable. Thus the stable operating region is from $\delta = 0$ to $\delta = 90°$. When the system is operated in this region, the system is said to be stable in the steady–state stability sense.

However, the system can not be operated close to $\delta = 90^\circ$ as any large load change in the system may cause the operating point to move across $\delta = 90^\circ$. In practice, the system is always operated with some steady–state stability reserve, which is normally expressed as the maximum ratio of P/P_{max} (approximately 0.6) or maximum δ (approximately 30°) allowed.

The above analysis shows that the maximum electric power which can be transmitted in such a system with a given steady state stability level is determined by the system voltage level and the "X" value. To increase the maximum power that can be transferred by such a system, "E_g" and "E" should be increased and/or "X" should be decreased.

The growing electrical load and the limited availability of "right–of–way" often require maximum utilization of each "right–of–way" in transmitting energy. Furthermore, technical and economic considerations tend to dictate a very high energy transmission per circuit. Increasing transmission capacity per circuit has been obtained traditionally by higher transmission voltages and higher speed breakers.

Once the structures and the conductors used by a transmission line are determined, the total "X" of the line increases as the transmission distance increases. This means that for a given voltage level, the maximum power that can be transmitted by this line reduces as the transmission distance increases. To keep transmitting the same amount of power for a longer distance under this condition, a higher voltage level is used.

As long distance power transmission usually involves bulk power transmission at the same time, raising the voltage level is the most effective way to increase the maximum power transferred for newly installed transmission systems. As equation (2.2.1) shows, doubling the voltage level of E_g and E could result in the maximum transferred power being quadrupled.

Another major advantage in using a higher transmission voltage level is that it can effectively reduce the transmission losses. This is not difficult to understand. When the same amount power is transferred, the higher the voltage is the lower the current will be, since power is the product of voltage and current. The total transmission losses "I^2R" are due to the heat generated by the current "I" flowing through the total resistance "R" of a transmission line. For the same transmission line transmitting the same amount of power, doubling the voltage level could half the current flowing through the line, reducing the losses to 1/4 of that at the lower voltage level.

For the above reasons, the voltage levels of long distance power transmission lines have been increased steadily from 110 kV to 750 kV in the past few decades. The use of even higher voltage levels, such as 1000 kV, is also under study.

Reducing the transmission system's "X" can also increase the transmission capacity of the system. However, it is not as effective as increasing the transmission voltage level of the system, since reducing the "X" by half only results in the transmission capacity of the system being doubled.

Though not as effective as raising the transmission voltage level, there are many situations where reducing "X" should be considered. This may come from the need to increase the transmission capacity of an existing transmission system for which the transmission voltage level has been fixed. In this case, both adding another parallel line or installing series capacitors could be considered to reduce the system "X" to increase the transmission capacity of the system.

§ 2–3 Series compensation versus other "X" reduction methods

Different techniques can be used to reduce the total system "X" of a transmission system to increase the system transmission capacity, such as reducing the reactance of the generators and transformers, adding intermediate switching stations to a parallel line transmission system, adding another parallel line to the existing system, and installing controllable and non–controllable series capacitors etc. Recently, environmental concerns have prompted utilities to actively investigate some other "X" reduction techniques which utilize the existing transmission system's corridor. These include building another parallel line on the same corridor and converting an AC transmission system to DC transmission system. Among these techniques, series compensation has been proven to be the most economic and effective means to reduce the "X" of a transmission system.

For generators and transformers, the amount of their reactance which can be reduced is very limited. It can only be reduced at the design and manufacturing stage. The reactance of an installed generator or transformer can not be changed.

Adding intermediate switching stations to a parallel line transmission system does not reduce the system "X" at the normal operation condition, but reduces the after–fault system "X" which increase the system transient stability level. This can be understood by the following example. Assume there is a parallel line transmission system having N lines in parallel with the same reactance "X_L" for each line. Without an intermediate switching station, a fault in the system requires the faulted line to be tripped. Tripping off a faulted line in this system will cause the total system reactance to increase from X_L/N to $X_L/(N-1)$. When a switching station is added at the middle point of the system, it divides the system to two sections, each with a system $X_{section} = X_L/2N$. A fault in such a system only requires the faulted line in one of the two sections to be tripped, causing the total system "X" to increase from $(X_L/2N + X_L/2N)$ to $(X_L/2N + X_L/2(N-1))$, which is less than $X_L/(N-1)$. Thus, adding an intermediate switching station is not very effective in reducing the system "X" and it also requires substantial capital investment.

Adding a parallel line at a single line transmission system can effectively reduce the total system "X" to half. However, it involves a large capital investment in towers, conductors, transformers and circuit breakers as well as the installation expenditures, and usually requires a new corridor or right–of–way for the new line. It also takes a significant amount of time in planning, designing and building a new line.

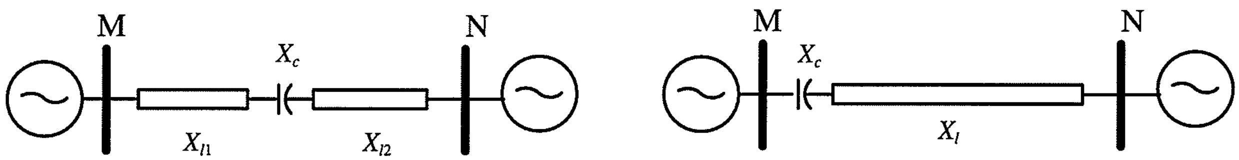
Adding a parallel line in the same corridor or converting an AC transmission system to a DC system may be used to increase the transmission capacity of the system while using only the existing corridor. However both have their drawbacks. Unless it was designed to add another line later to the same corridor, adding a parallel line to an existing corridor is more difficult than building a parallel line on another corridor. Extra effort and investment will be needed to reconfigure the existing system and to build the new line while the existing lines are operating. Converting an AC system to an DC system would require the transformers and breakers of the existing system to be replaced and the installation of AC–DC convertors and invertors.

On the other hand, series compensation can be as effective as adding a parallel line in reducing the system "X" while requiring much less capital investment. For a single line transmission system, it only requires the installation of capacitor banks at one (either at one end or the middle point of the line) or two (both ends of the line) locations on the line to reduce the "X" by half. Though the circuit breakers of the line may need to be upgraded and a new transformer may need to be added, the total installation cost of series compensation is still much lower than adding a parallel line.

Also, the series compensation could have other advantages, such as its application in load flow distribution control. In the past, the load flow distribution of a power system can only be controlled by adjusting the bus voltage magnitudes and the transformer tap changers, since the system impedance matrix can not be changed. Since the bus voltage magnitude must be within an allowed margin (± 10%) and the range of a transformer tap changer adjustment is limited, system load flow regulation is restricted and some load flow distributions are impossible to achieve. When controllable series capacitors (i.e. the impedance of these series capacitors is controllable) are installed in the system, it can greatly improve the controllability of the system load flow distributions. One simple example can illustrate the above point. For two lines in parallel (with identical line impedance, the same type of controllable series capacitor and the same bus voltage at both ends), they can carry different amounts of load flow if they are controlled to have different degrees of compensation.

§ 2–4 Types of series compensated transmission lines

A transmission line can be series compensated in several ways. When a transmission line is series compensated at a single location, it is normally placed either at one end of the line, or in the middle of the line, as shown in Fig. 2.4.1 While the middle–compensation is more effective [3], an end–compensation offers easy installation and maintenance, and has less problems in line protection as will be discussed later.



(a) at the middle of a line (b) at one end of a line

Fig. 2.4.1 A transmission line compensated at one location

In some cases, a line could be series compensated at two locations. Normally, the two capacitors are put at opposite ends of the line, with each capacitor having half of the required "X"$_c$, such as shown in Fig. 2.4.2

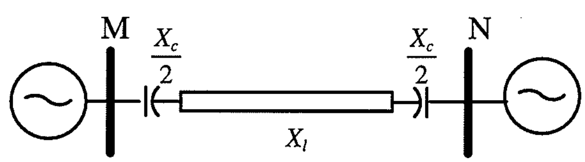


Fig. 2.4.2 A transmission line compensated at both ends

The reduction of line impedance is usually measured by the degree of compensation. The degree of compensation of a series compensated line is defined as

$$k_{comp} = \frac{X_c}{X_L} \times 100\% \qquad (2.4.1)$$

where X_c is the reactance of series capacitor and X_L is the line reactance without compensation.

§ 2–5 Protection circuits required for series capacitors

While effectively reducing the inductive line reactance, the series compensation causes the short circuit current levels of the compensated line to increase due to the reduction of "X". Fig.2.5.1 illustrates the problem. The equivalent transient EMF of both cases are assumed to be the same at 1.0 pu, and "X"$_c$ = "X"$_l$/2 = 0.5 pu.

(a) Without series compensation (b) With series compensation

Fig. 2.5.1 Effect of series capacitor in increasing short circuit current

In Fig.2.5.1, for a three–phase fault at the same location (i.e. same "X"$_1$), the short circuit current of case (b) is $I = 1.0/(1.0 - 0.5) = 2\ pu$, which is twice as much as $I = 1.0/1.0 = 1\ pu$ in case (a).

The high fault current generates a high voltage across the series capacitor. To design series capacitors to sustain the highest fault current level is not economic. Protection circuits are commonly provided to by–pass the series capacitor during the high fault current period. These protection circuits will operate to by–pass the series capacitor when the voltage across the capacitor exceeds their safe operating level. With the assistance of this protection circuit, series capacitors with lower voltage rating can be used, reducing the cost of the series capacitors.

Early series capacitor protection was carried out by a single spark gap with a by–pass switch scheme as shown in Fig.2.5.2. When the voltage across the capacitor reaches the sparkover voltage level of the gap, a spark will be ignited which by–passes the capacitor. As the voltage across the capacitor reduces (while it is by–passed), the spark could not be maintained resulting in immediate reinsertion of the capacitor. Reinserting the capacitor before the fault is cleared and the gap is cooled down, will cause a so called re–spark problem. Closing a by–pass switch at the same time as the initial spark is ignited keeps the capacitor by–passed, which solves this problem (it takes a longer time delay for a by–pass switch to effectively by–pass the capacitor than a spark gap does). After the voltage across the capacitor drops to below the setting and the spark gap is sufficiently cooled down, the by–pass switch is re–opened and the capacitor is reinserted into the line. Typical reinsertion time (considering spark gap cool down for a single gap protection scheme) is in the range of 300 – 400 ms [14]. A damping circuit between the capacitor and the spark gap limits the current through the gap when it ignites.

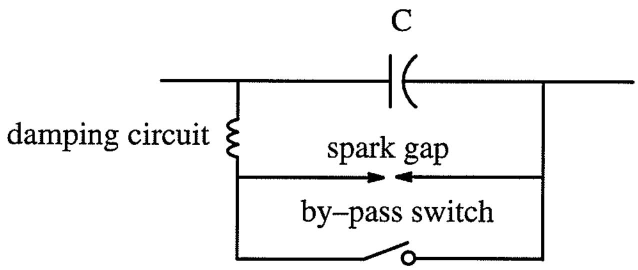
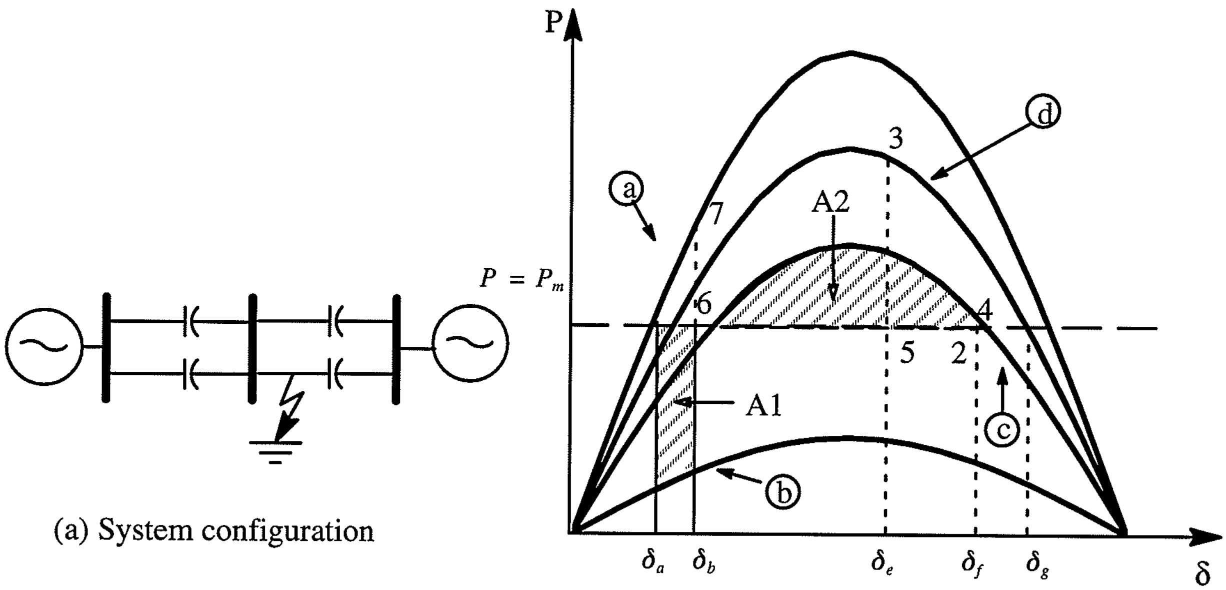


Fig. 2.5.2 Single–gap single–switch series capacitor protection scheme

The sparkover voltage setting is normally 2.5 – 3.0 pu with 1.0 pu corresponding to the series capacitor's voltage at its nominal current. The sparkover voltage level should not be designed at a lower level, since this may cause series capacitor by–passing at the current levels associated with rotor angle oscillations in a power system. The by–passing of capacitors under such conditions has an adverse effect on the system, since it reduces the system stability level.

The long reinsertion time of a single–gap protection scheme results in a low system transient stability level. Fig.2.5.3 illustrates the point. In Fig.2.5.3 , curve (a) and (b) are the P–δ relationship before and during the fault. Curve (c) represents the P–δ relationship after fault clearance and without series capacitor reinsertion, while curve (d) is with series capacitor reinsertion. Clearly, reinsertion of series capacitor on the unfaulted line sections immediately after fault clearance increases the deceleration area A2, thus increasing the system transient stability level.



(a) System configuration

(b) P–d curves under different conditions

Fig. 2.5.3 System transient stability level as affected by long reinsertion time

To shorten the reinsertion time, a double–gap double–switch scheme is used in some applications (Fig.2.5.4). The spark gap G2 has a lower sparkover voltage setting than spark gap G1. The series switch is always closed during normal operation.

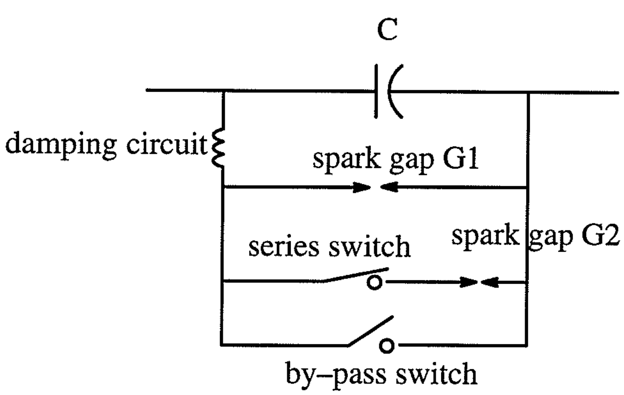


Fig. 2.5.4 Double–gap double–switch series capacitor protection scheme

When the voltage across the capacitor exceeds the G2 setting, G2 will be ignited and the by–pass switch is closed. The series switch opens after the by–pass switch is closed, preventing the re–sparking problem of G2 caused by the by–pass switch opening to reinsert the capacitor before it is cooled down. The spark gap G1 functions as a back–up protection. If capacitor overvoltage occurs before the series switch is re–closed, G1 will ignite to protect the capacitor and re–close the by–pass switch. The double–gap double–switch scheme can have a reinsertion time of about 100 ms.

The development of ZnO Metal Oxide Varistors (MOV) further improves the protection of series capacitors and reinsertion time. An MOV has a voltage–current characteristic as shown in Fig.2.5.5 , and a series capacitor protected with an MOV is shown in Fig.2.5.6

$$i = \left[\frac{v}{V_N}\right]^n$$

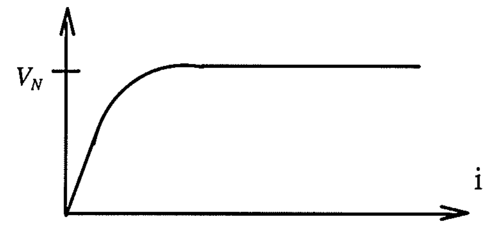


Fig. 2.5.5 Typical MOV voltage–current characteristic

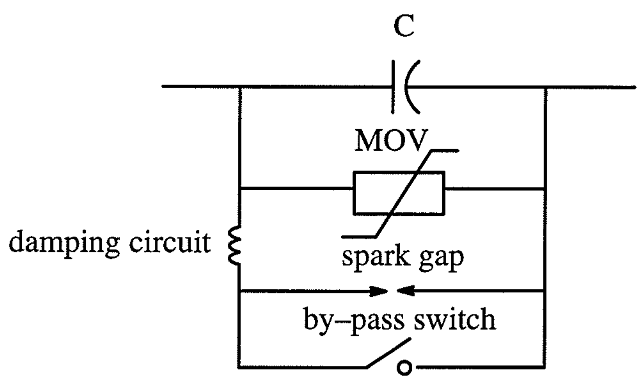


Fig. 2.5.6 Series capacitor protection using MOV

Unlike the spark gap, the MOV operation is based on the instantaneous voltage across the capacitor. Whenever the instantaneous capacitor voltage level exceeds V_N, the MOV will be switched on to divert part of the current from the capacitor so that the capacitor voltage level can be controlled. Also, the capacitor is reinserted almost instantaneously after the capacitor instantaneous voltage is reduced to below V_N. This results in a partial by–pass or an intermittent conduction of the MOV [1] [4] [8], as can be seen in Fig.2.5.7 .

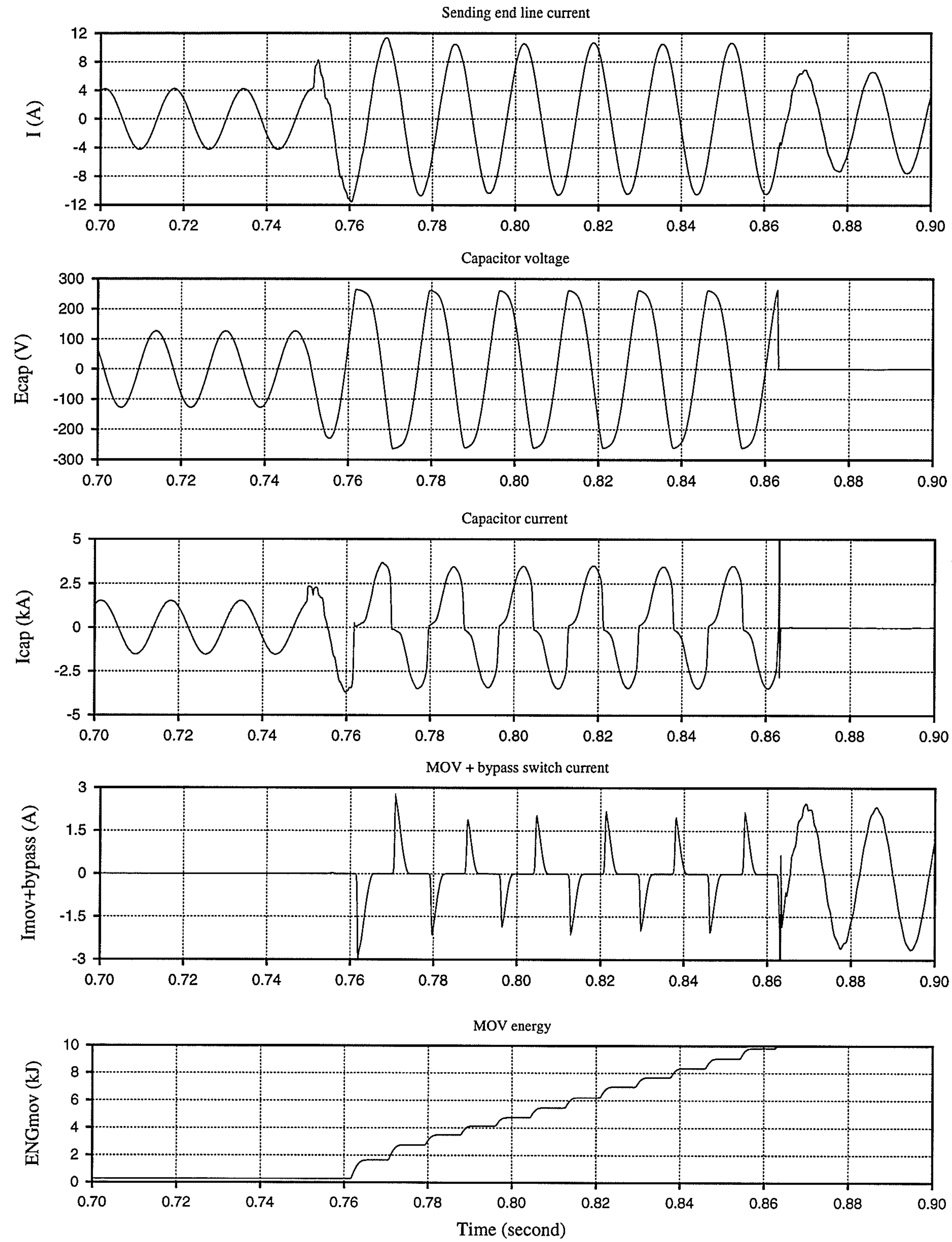


Fig. 2.5.7 Voltage and current waveforms in a series capacitor and an MOV

A partial by–pass leads to the partial retention of series compensation under non–severe faults, which has a positive effect on the transient stability during the by–pass period. Furthermore, an MOV protected series capacitor allows almost instantaneous reinsertion of the capacitor after a fault is cleared.

The main restriction of using only an MOV to protect a series capacitor is its cost, although the technical advantage of using an MOV to protect a series capacitor is evident. When an MOV is by–passing a capacitor, a large amount of energy is absorbed by the MOV and a large amount of heat will be generated, since an MOV is a pure resistor while conducting. The cost of an MOV is directly related to its energy absorption capacity. To allow for some cost reduction, an MOV should be specified to take into account only external faults of the compensated line section and the related energy levels. When the energy absorption level of an MOV is designed in this way, the internal faults in the compensated line section may cause the energy level to be exceeded. A spark gap and a by–pass switch is provided to by–pass the capacitor and the MOV whenever the specified MOV energy level is exceeded during an internal fault to protect the MOV.

The long reinsertion time of the single–gap single–switch scheme in this case does not affect the transient stability level of the transmission system, since the faulted line has to be tripped to clear the fault, and when it is reclosed on a temporary fault, the gap already has had enough time to cool down.

Because of these reasons, the protection scheme shown in Fig.2.5.6 has been widely used in new series capacitor installations.

CHAPTER 3:

PROBLEMS IN THE PROTECTION OF SERIES COMPENSATED LINES

§ 3–1 Introduction

The protection systems used for HV/EHV transmission lines can be divided into the following two basic categories: pilot protection systems and non–pilot protection systems. The definitions for pilot and non–pilot protection systems used here are in the general sense. A pilot protection system takes measurement at both ends of a line and uses communication channels to exchange information with each end. The breaker trip signal is generated according to the information obtained from both ends. A non–pilot protection system generates the tripping signals according to the information of only the one end where the measurement is taken. A pilot protection system costs more than a non–pilot system as it requires the support of communication equipment.

From the transient stability point of view, the protection systems of an HV or EHV transmission line should operate as fast as possible to reduce the acceleration energy of a fault (refer Fig. 2.5.3). The pilot protection systems, though they can generally provide satisfactory performance in clearing any fault in the protected lines, are known to add 1/2 to 1 cycle communication time to a typical zone1 trip time. This is due to the extra time delay introduced by the communication channels. The pilot protection systems also have a lower reliability level due to the inclusion of communication channels. Therefore providing a non–pilot protection system along with the pilot protection system to provide an overall fast relay operating time over 60%–70% of the line length and an increased reliability level is a common practice among utilities.

Generally, a pilot protection system can classify the internal faults and external faults more easily than can a non–pilot system. Protection systems are installed at both ends of a transmission line, and for each of them the line side is considered as the forward direction and the bus side as the reverse direction. In a pilot protection system, the most important information it needs is the direction of a fault, i.e. if the fault has occurred in the forward direction or in the reverse direction. When both sides "see" a fault in the forward direction, that means the fault is on the protected line section and trip signals will be generated to trip the breakers of both ends. Under all other conditions, no trip signals will be generated.

However, in addition to the fault direction information, a non–pilot protection system must determine approximately where the fault is. This is because a fault in the neighboring line section adjacent to the protected line section can also be seen as a forward direction fault. Thus the "distance" of a fault from the fault location to the relay site should be known for the correct operation of a non–pilot protection system.

Series compensated lines have always been known to require special protective relays and schemes. Generally, series compensation causes less problems for a pilot protection system than for a non–pilot protection system. This is because the presence of a series capacitor does not greatly affect many commonly used fault direction detection algorithms, but causes difficulties in the "distance" calculations. As stated in [2], two different pilot relay schemes have been predominantly used to protect series compensated lines. One scheme uses current phase comparison and the other scheme uses directional comparison designed specifically for series compensated lines. In this thesis, the fault direction detection problem for a series compensated line is assumed to have been properly resolved. The focus will be on the analysis of major difficulties in the fault "distance" measurement for a series compensated line and how to overcome these difficulties.

Two types of relays can be applied in the fault distance measurement for a non–series compensated transmission line: overcurrent relays (including phase current and sequence component current) and impedance relays (sometimes called voltage/current ratio relays). The overcurrent relays will not be discussed in this thesis, as the accuracy of distance measurement for an overcurrent relay is greatly affected by the system operating conditions. On the other hand, impedance relays are widely used in the HV/EHV transmission systems without series compensation, since their operation is not affected by the system operating conditions. However, the application of series capacitors change the impedances seen by the impedance relay. This causes problems in the correct operation of the impedance relays. Thus the focus of this thesis will be to study the problems of impedance relays caused by series compensation and to develop an adaptive impedance relay to properly protect a series compensated line.

In the following sections, the typical characteristics of impedance relays, the coordination of impedance relay zones, and the problems caused by series compensation on an impedance relay will be presented and studied in detail to provide a background for later analyses.

§ 3–2 Typical impedance relay characteristics

Fig.3.2.1 shows a transmission line without series compensation protected by an impedance relays at both ends. The typical characteristics of the MHO circle relay and quadrilateral relay are shown in Fig.3.2.2

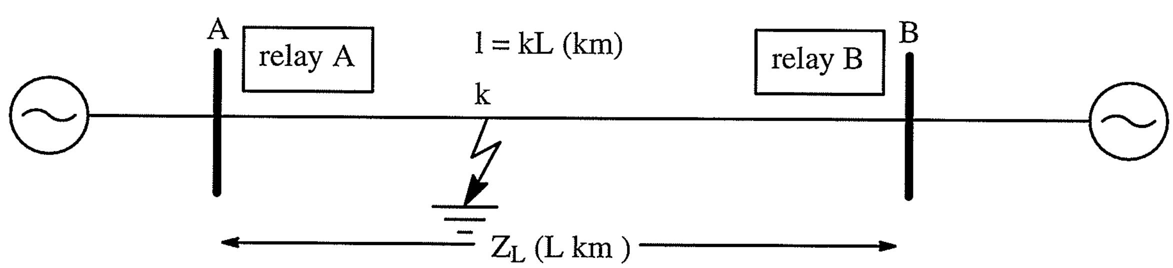


Fig.3.2.1 Transmission line without series compensation

In the Fig. 3.2.2, Z_L' is the following line's impedance and the line O–Z_L–Z_L' represents the transmission line's impedance trajectory seen by the impedance relay.

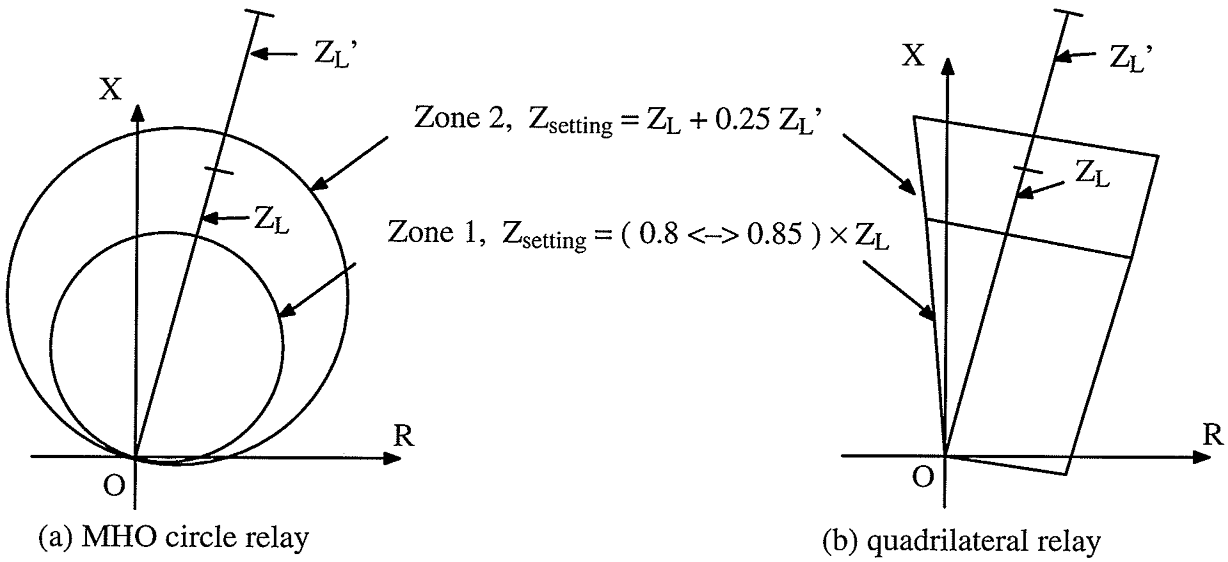
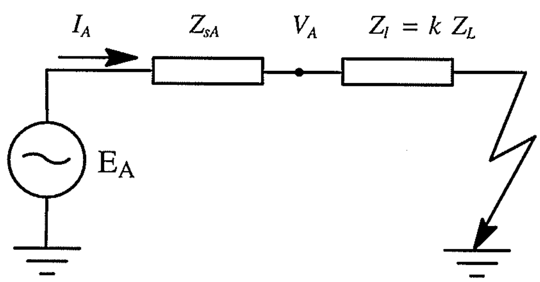


Fig. 3.2.2 Typical impedance relay characteristics

The following example shows why an impedance relay can be used to measure the fault distance. Assume the line length is L and the total impedance of the line is Z_L. When a three phase fault occurs at l = kL km from the bus A (the impedance between bus A and fault location is $Z_l = k Z_L$), the impedance seen by relay A can be calculated using the single phase diagram of Fig. 3.2.3 (since it is a symmetrical fault).



as $I_A = \dfrac{E_A}{Z_{sA} + Z_l}$

and $V_A = \dfrac{Z_l}{Z_{sA} + Z_l} E_A$

==> $\dfrac{V_A}{I_A} = Z_l$

Fig. 3.2.3 Fault impedance calculated from the A side

Since the ratio of Z_l to Z_L is k, the fault distance from bus A to the fault location can be obtained by multiplying total line length L with the ratio k. The same is true for the relay at bus B, but the fault distance seen by relay B will be (1 – k)L instead of kL.

Normally when a fault occurs, the impedance relay compares the measured impedance with the preset settings and generates a trip signal if the fault is within its operating area as shown in Fig. 3.2.2. As can be seen from the diagram, the operating zones of both impedance relays have large areas at the right side of the $O–Z_L–Z_L$' line. This is because a fault with fault resistance will cause the impedance seen by the relays to fall into that area. An impedance relay with such a shaped operating zone will be able to operate correctly under fault conditions with a certain amount of fault resistance.

Fig. 3.2.2 shows that an impedance relay has two zones, zone 1 and zone 2. In fact, many impedance relays have another zone, i.e. zone 3. The line sections which are protected by these three zones of an impedance relay are shown in Fig. 3.2.4

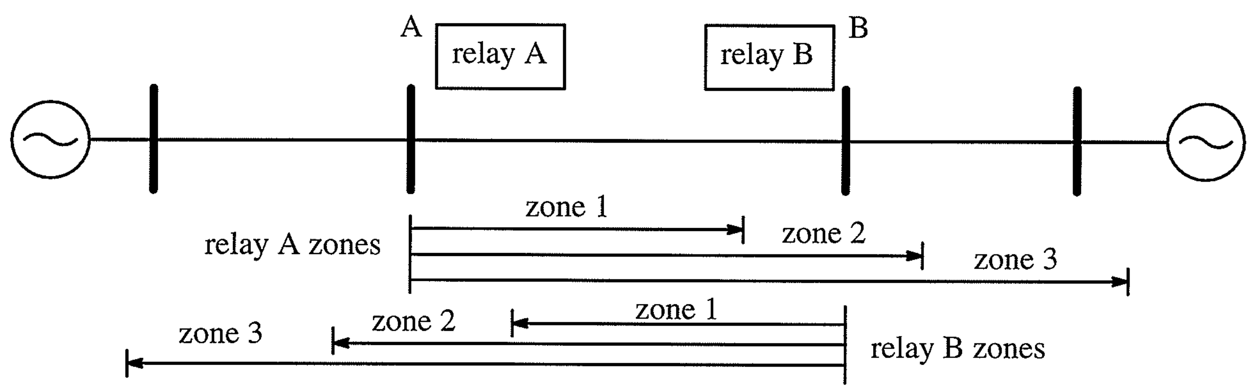


Fig. 3.2.4 Typical impedance relay zone coverages

The operating times for these zones are different. Zone 1 operates immediately after the fault impedance locus enters the zone. Zone 2 operates with a time delay of about 0.5 sec. and zone 3 has an even longer time delay (> 1.0 sec.).

The reason for an impedance relay to have three different operating zones and different operating times is to ensure the correct selection and isolation of a faulted line section and at the same time to provide remote back–up protection for the adjacent line sections. The purpose of a remote back–up protection scheme is to ensure the faulted adjacent line sections can be isolated from the system in case the relays and breakers on these line sections fail to trip.

The zone 1 provides the main protection of the line section where relay is installed, as it trips for a fault on this line section immediately. It only covers 80 – 85% of the length of the protected line section. This is due to several factors which have to be taken into account to avoid tripping on the faults occurring at adjacent line sections (over–reach tripping). The factors which may cause an over–reach problem are the measurement and calculation errors of the relay, remote source current effect on faults with fault resistances, fault induced transients, and non–perfect CT and PT characteristics. Line impedance varies with the weather conditions and the system operating frequencies, as well as errors in relay settings.

Thus for faults occurring at both ends of a line where impedance only falls into one relay's zone 1, only one breaker at one end of the line will be operated by that relay. To provide fast protection for those faults occurring on the protected line section which are not covered by zone 1, zone 2 is used. Zone 2's settings not only cover 100% of the line section it protects, but also extend to about 25% of the adjacent line section. This guarantees that all the faults on a protected line section will be detected and cleared even under the worst under–reach conditions. The under–reach problem is also caused by those same factors mentioned above which cause the over–reach problem.

Combined zone 1, zone 2 and a communication link provide a line section with overall fast fault clearance ability. When a fault occurs at the middle of the line, the zone 1 of the relays at both ends will operate. For faults occurring at the locations close to one end of the line, the breaker at this end will be operated by the zone 1 of the relay at this end, while the breaker at the opposite end will be operated by the local zone 2 plus the pilot signal from the other end.

Zone 3 is mainly for remote back–up purposes. Relays and breakers on the faulted line section may fail to trip the faulted line section due to various reasons. Zone 3 can detect a fault on the adjacent line section. In other words, if a fault occurs on a protected line section it will be detected by the zone 3 of the relays on the adjacent line sections. Thus, if after a specified time delay the relay zone 1 and 2 and the breaker on the faulted line section fail to clear the fault, the fault will be cleared and isolated from the system by the action of the adjacent line sections' relay zone 3 and its breaker. Fig. 3.2.4 shows only a single adjacent line section beyond the protected line section. When there are more than one line sections beyond the protected line section, the zone 3 setting should be chosen to cover the longest adjacent line section.

The above description shows that zone 1 and 2 of an impedance relay are the two most important zones for fast and reliable protection of a protected line section. Combined, they should provide 100% protection of the protected line section and clear the faults on this line section as fast as possible to limit the damage to the line and increase system's transient stability level.

§ 3–3 Basic problems in protecting series compensated lines

Some problems in the protection of series compensated lines using impedance relays have been studied previously [7] [8] [12]. In these studies, the problems of the conventional impedance relays caused by a series capacitor and its protection circuits are investigated, such as the effect of the series capacitor location, the relay PT location and the partial conducting characteristic of an MOV series capacitor protection circuit. As shown in these studies, due to the complexity of the problems, it is beyond the ability of conventional impedance relays to solve these problems properly. Developing an adaptive impedance relay could be a solution to these problems for which a thorough understanding of some other problems caused by the series compensation is very important.

Using impedance relays to protect series compensated lines encounters several problems caused by different factors. These problems are (1) a spiral impedance locus caused by the sub–synchronous oscillation transients between the series capacitor and line impedance initiated by a fault, (2) the measured line impedance not being in proportion to the line length due to series capacitors, (3) the need to change relay settings when the system operating conditions change, and (4) the dynamically changing equivalent series capacitor impedance during a fault due to the action of its protection circuits.

The first problem is that a sub–synchronous transient oscillating component causes the impedance locus seen by the impedance relay to spiral, as can be seen in Fig. 3.3.1.

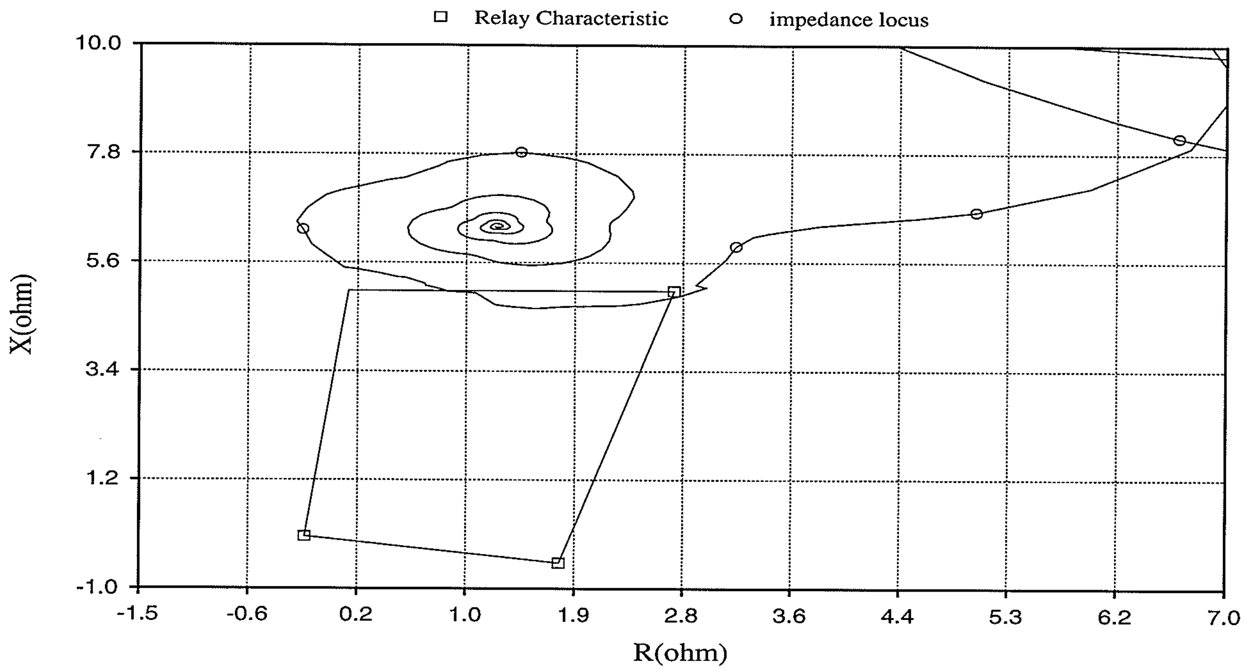


Fig. 3.3.1 Spiral impedance locus caused by the sub–synchronous transient component

This will cause relay operation delay for faults inside the operating zone or misoperation of the relay for faults outside the zone when these faults occur at locations close to the boundary of the relay operating zone. However, this problem can be solved by utilizing a high–pass filter which does not allow the sub–synchronous component to pass. Fig. 3.3.2 shows a filtered impedance locus of the same fault. Thus this problem is assumed to be resolved and will not be further discussed in this thesis.

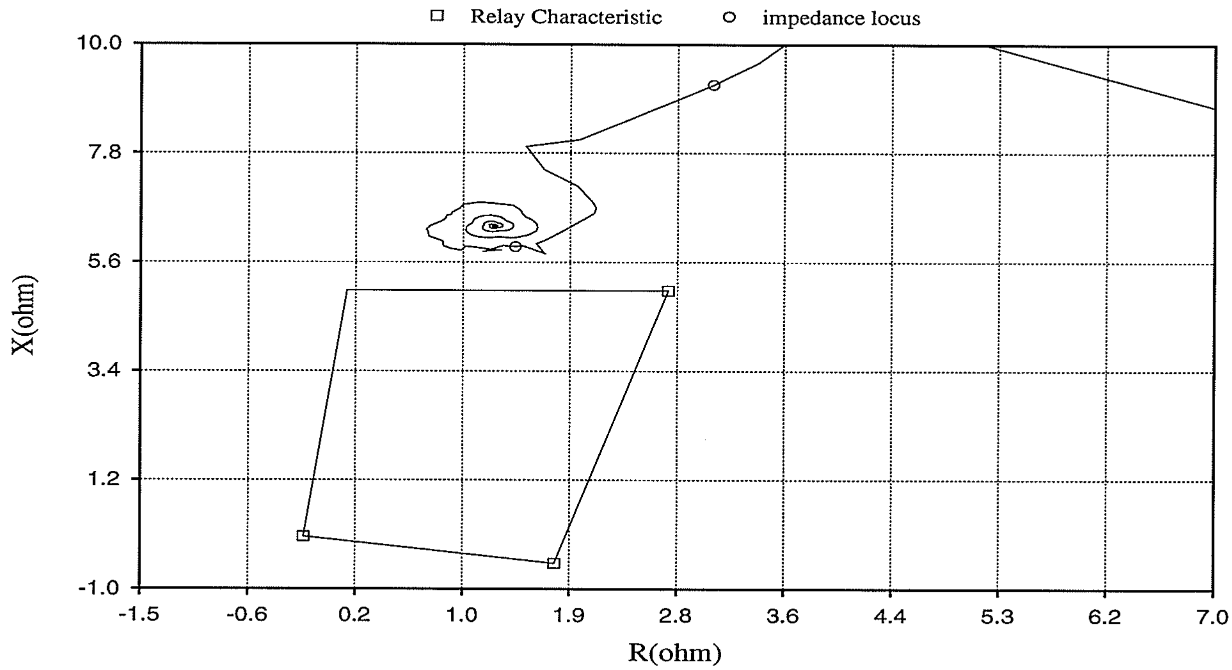


Fig. 3.3.2 Impedance locus after filtering

The remaining problems have different difficulties to solve. Their solutions are affected by various factors, such as the location of a series capacitor. In the following sub–sections, these problems will be investigated and discussed in detail.

§ 3–3–1 Problems caused by the use of series capacitor

When the system operating conditions change and the actions of the series capacitor protection are not considered, the problems caused by the series capacitor are closely related to these factors: the degree of the compensation, the location of the capacitor and the location of the relay PT.

As mentioned in the previous chapter, a series compensated line has three different capacitor locations: at one end of the line, at the middle of the line and at both ends of the line. For capacitors at one end or both ends of the line, the problems caused by the series capacitor are the same. Thus only the one end and the middle of the line cases will be discussed.

When a series capacitor is placed at the one end of a line, there are three possible relay PT locations: at the line side of the capacitor, between the breaker and the capacitor, and between the bus and the breaker (locations (a) (b) and (c) shown in Fig. 3.3.1.1). The last two locations have the same effect on the impedance relay, thus they are considered as one alternative: at the bus side of the capacitor.

Fig. 3.3.1.1 shows an end–compensated line with the PT placed at the bus side of the capacitor. The diagram also shows the line impedance seen by the relay during the forward three–phase faults. When the series capacitor and relay PT are placed at such locations, the relay does not have problems during the reverse faults, since the impedance seen by the relay will be the same as without series compensation.

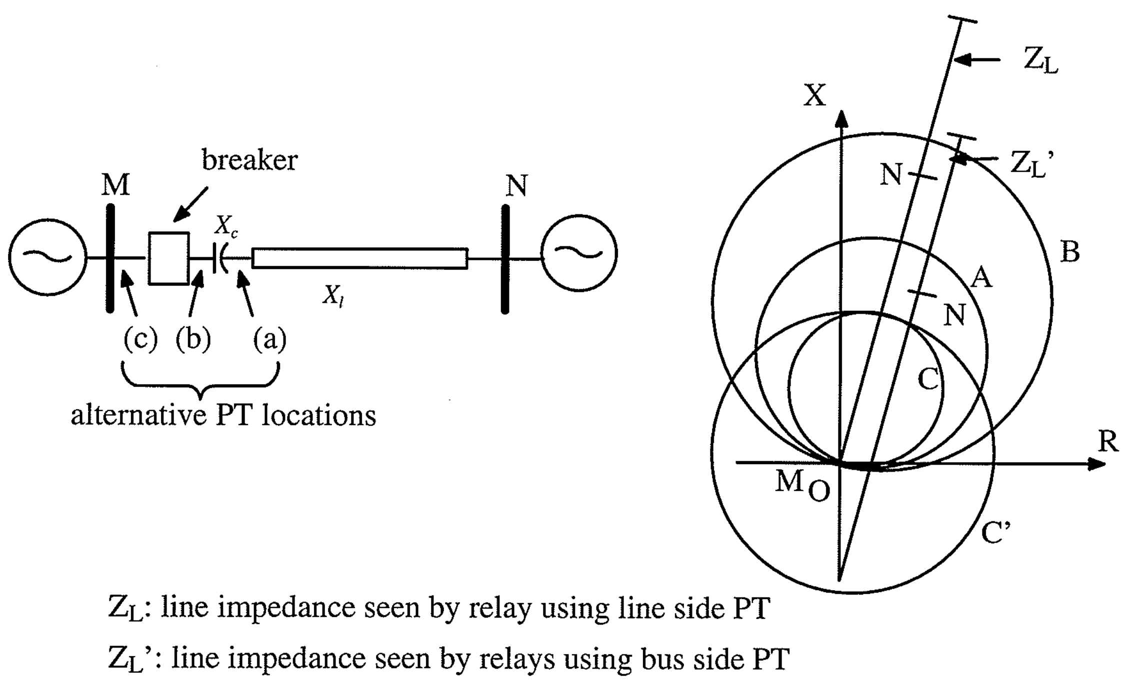


Fig. 3.3.1.1 Line impedance seen by the relay for an end–compensated line

As can be seen from Fig. 3.3.1.1, one problem for the impedance relays when a series capacitor is used and the PT is placed at the bus side of the capacitor is that the relay setting must be adjusted. If the setting is not adjusted, zone 1 of the relay will operate for faults on the adjacent line section close to the remote bus of the line, as the reactance of the series capacitor cancels part of line inductance. Normally the settings to avoid these over–reach problems caused by the series capacitor can be adjusted to as follows:

$$Z_{setting} = (0.8 \leftrightarrow 0.85) \times (Z_L - X_C) \qquad (1.1)$$

The circle C is the new zone 1 operating area. The new setting still has two problems. One is the reduced fault resistance tolerance. This problem can be solved by utilizing quadrilateral relay characteristics. The other problem is more severe as can be seen from the diagram. A fault close to the capacitor will be seen by the relay as a "reverse" fault. This will cause the relay to fail to operate and will affect both the zone 1 and zone 2 of the relay.

However, this problem can be solved by extending the relay operating zones in the reverse direction and adding an effective fault direction detection circuit. This is shown as circle C' in the Fig. 3.3.1.1

When the relay PT is placed on the line side of an end–compensated line, the problem is opposite to the previous case. The line impedance seen by the relay will be the same as the line without the compensation during the forward faults, thus the settings of the relay should not be adjusted. But a reverse fault close to the bus will be seen as a "forward" fault due to the effect of the series capacitor. Once again, this problem can be easily solved by adding an effective fault direction detection circuit.

Comparing these two cases, placing the relay PT on the line side of the capacitor poses less problems than placing it on the bus side of the capacitor, as there is no need to change relay settings. Also in the above two cases, the degree of the compensation has no major effect on the problem being discussed.

When a series capacitor is placed at the middle of a line, there will be no alternatives for relay PT locations. This time the bus side of the capacitor is the only choice. The line impedance seen by the impedance relay will be changed to the one as shown in Fig. 3.3.1.2

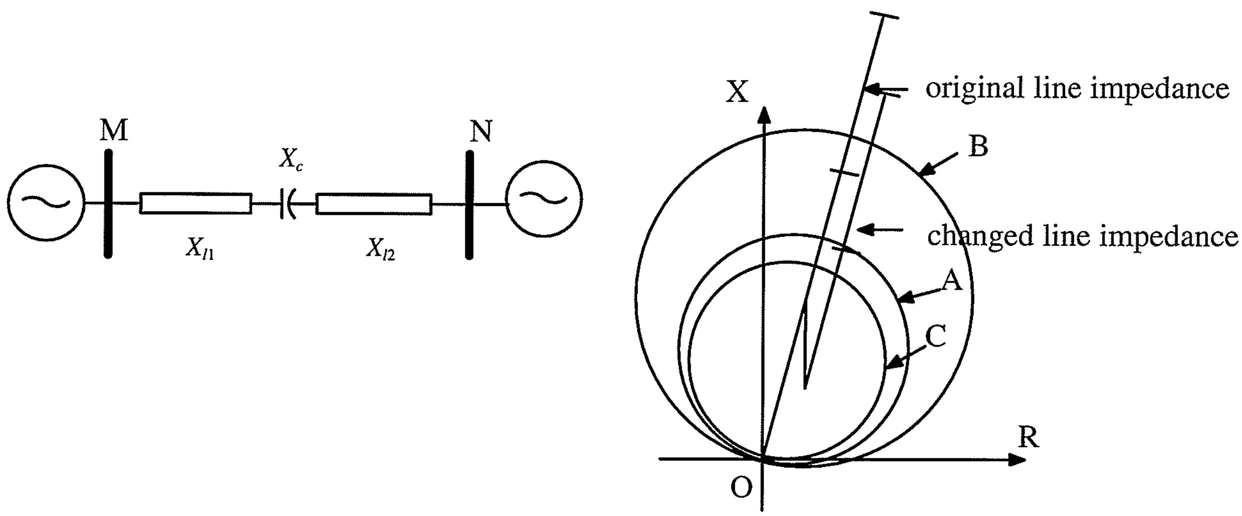
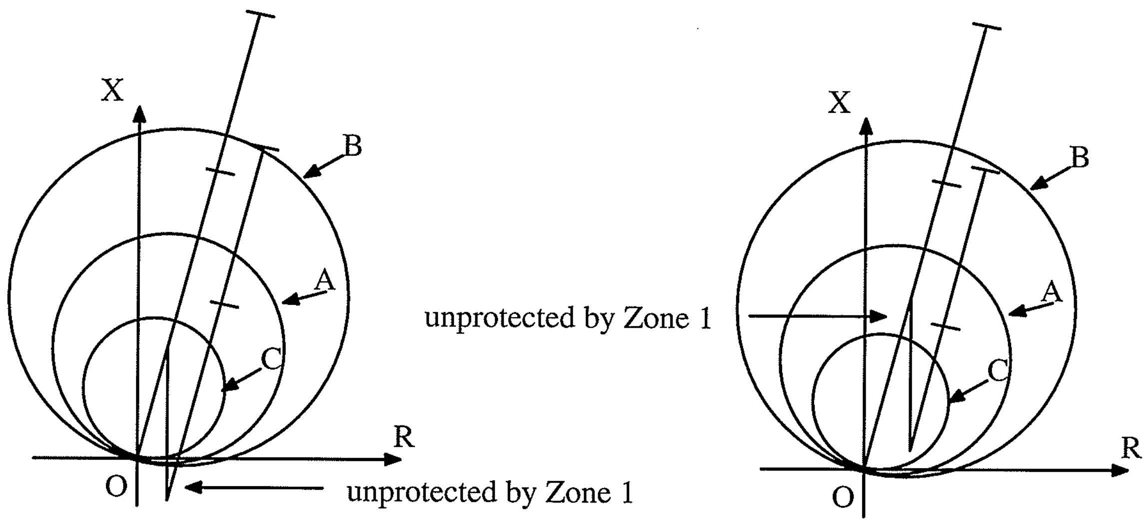


Fig. 3.3.1.2 Line impedance seen by the relay on a low–degree mid–compensated line

For this case, a relay setting change is necessary (circle C) and the degree of compensation will create problems for the relay. When the compensation degree is low, the zone 1 setting calculated by equation (1.1) will provide the proper coverage of the protected line section (Fig. 3.3.1.2). For a MHO circle characteristic, this reduces the fault resistance tolerance of zone 1. However, this can be solved by utilizing quadrilateral characteristics. Unfortunately if the compensation degree is high (> 50%), another problem will arise.

As shown in Fig. 3.3.1.3, part of the line section close to the series capacitor will not be covered by the zone 1 of the relay. The problem is affected by the exact capacitor location. When the capacitor is close to the relay location, the unprotected part is as shown in Fig. 3.3.1.3 (a). This problem could be solved by extending the zone in the relay's reverse direction and adding an effective fault direction detection circuit. If the capacitor is located beyond the middle point of the line (from the relay site point of view), the unprotected part is as shown in Fig. 3.3.1.3 (b). This problem can not be solved by extending the zone 1 in the forward direction, as it will cause an over–reach problem. For a capacitor located very close to the exact middle point of the line, both problems will occur due to further reduced zone 1 setting (refer to equation (1.1)).



(a) close to relay location

(b) beyond the mid–point

Fig. 3.3.1.3 Effects of capacitor locations for a high–degree mid–compensated line

When the capacitor is not located exactly at the middle point, it will be seen by the relay at one end of the line as a passing–over mid–point one and by the relay at the other end as a close to the relay site one. Thus the above mentioned problems will always exist for a high–degree mid–compensated line, regardless of the exact location of the capacitor.

The zone 2 of a relay is mainly affected by the forward fault seen as a "reverse" fault and the reverse fault seen as a "forward" fault problem. Both problems can be solved by the addition of a fault direction detection circuit. The problem in Fig.3.3.1.3 (b) normally does not cause problems for a zone 2 setting, as can be seen from the graph.

In conclusion, when a series capacitor is always operating in the line and the action of its protection is not considered, it does not cause major protection problems for the zone 2 of an impedance relay. It causes some problems for the zone 1 when the line is end–compensated, but these problems can be solved by a directional circuit. It does not cause problems for a low–degree mid–compensated line, but causes problems for a high–degree mid–compensated line. When the capacitor is located close to the relay site, the problem is solvable. However, when the capacitor is located beyond the middle point, the problem can not be solved, leaving that unprotected part to be protected by the zone 2 of the relay.

§ 3–3–2 Problems caused by change in the system operating condition

The previous section's conclusion does not consider a system operating condition change. The fact is that a series capacitor may not be in–service due to load flow control and other reasons. As a conventional relay can only have one setting, the system operating condition change causes more problems. These problems will be briefly analyzed as follows.

For an end–compensated line with the relay PT located on the line side of the capacitor, the capacitor being in–service or out–of–service has no effect on the relay setting. Thus it does not cause any problems for such cases.

When the line is end–compensated and the PT is located either on the bus side of the capacitor or the line is mid–compensated, the capacitor in–service or out–of–service condition will require the relay to use two settings to provide proper coverage for the protected line. If the relay can only have one setting, the capacitor out–of–service setting can not be used, as it will cause over–reach problems when the capacitor is in–service. But using the capacitor in–service setting will cause the following problems when the capacitor is out–of–service (Fig. 3.3.2.1) (the diagram shows only the zone 1 of the relays).

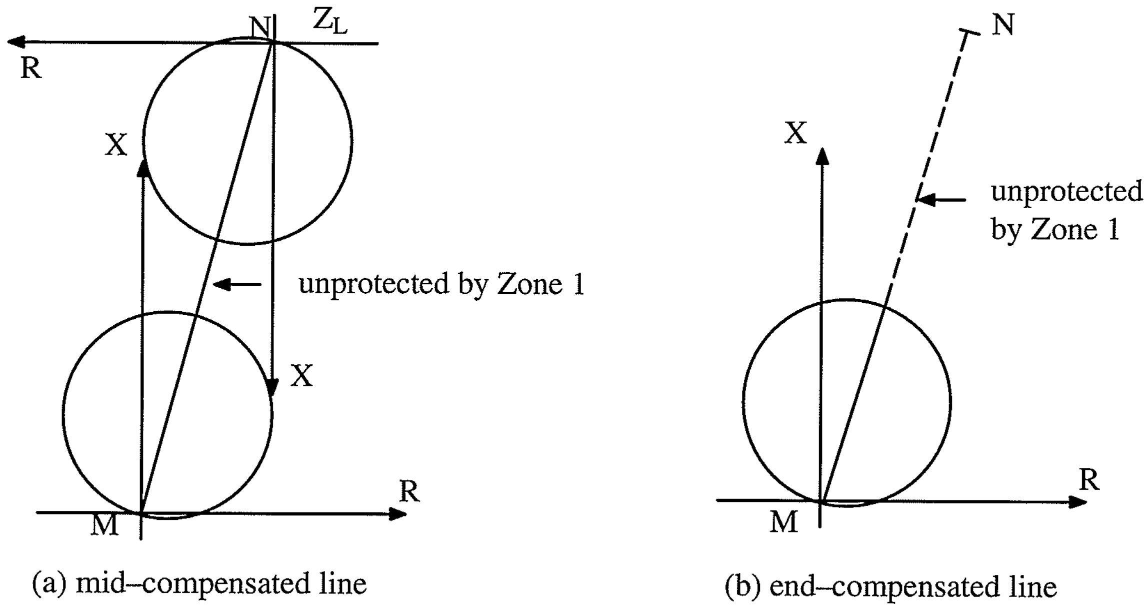


Fig. 3.3.2.1 Capacitor out–of–service when in–service settings are used

As can be seen from the diagram, capacitor out–of–service when in–service settings are used causes a reduced zone 1 coverage problem, which will result in the middle part of a mid–compensated line not being protected completely by the zone 1 of the relays. For an end–compensated line, it will affect the relay on compensated end(s) if a bus PT is used for the relays.

There is no easy solution for the above problem. The best way to solve the above problem is to adaptively change the relay setting according to the capacitor in–service status. For end–compensated lines, the relay may be able to get the capacitor in–service status to automatically adjust the relay setting, as this information may not be difficult to obtain. However, this information is difficult to obtain for a mid–compensated line without the help of communication links.

§ 3–3–3 Problems caused by the protection of series capacitors

The protection of a series compensated line using impedance relays is further complicated by the action of series capacitor protection circuits. To simplify the following analysis, a fault which occurs between the relay in question and the series capacitor is called a "fault in front of the capacitor", while a fault which occurs between the capacitor and the remote end of the line is called a "fault behind the capacitor". Also, only the protection circuits using MOVs for series capacitors will be discussed, as this is the predominantly used protection circuit for protecting series capacitors.

From the relay point of view, a fault occurring in front of a series capacitor does not cause major problems for the relay operation. The fault "distance" seen by the relay is the same as the one having no series capacitors. However, a "dynamic fault impedance variation" problem will arise when a fault occurs beyond the capacitor.

As was presented in the previous chapter, an MOV starts to conduct whenever the instantaneous voltage across the capacitor exceeds the turn–on voltage level of the MOV. The conduction of the MOV causes the equivalent impedance of the series capacitor and MOV seen by the relay to change as determined by the fault current level [8]. When the energy level of the MOV is reached, the by–pass switch of the capacitor will operate, resulting in the capacitor becoming completely out–of–service. Thus there will be three different scenarios.

Scenario one: the voltage level across the capacitor caused by the fault current is below the MOV conducting level. In this case, the problem is the same as analyzed in the previous sub–sections. This is unlikely to happen for faults occurring on the protected line section and the adjacent line sections, thus this will not be discussed further.

Scenario two: the voltage level is higher than that of the previous case, but the energy level of the MOV is reached only after a certain time delay (several cycles). Thus the relays at the protected line section or the adjacent line sections have enough time to clear the fault before the energy level is reached.

Scenario three: the fault current is so high that shortly (within 1 –2 cycles) after the MOV conduction, its energy level is exceeded thus causing the by–pass switch to operate. The impedance seen by the relay will be initially the one with MOV conducting and then become the capacitor out–of–service one, as can be seen from the Fig. 3.3.3.1 This is the so called "dynamic fault impedance variation" problem.

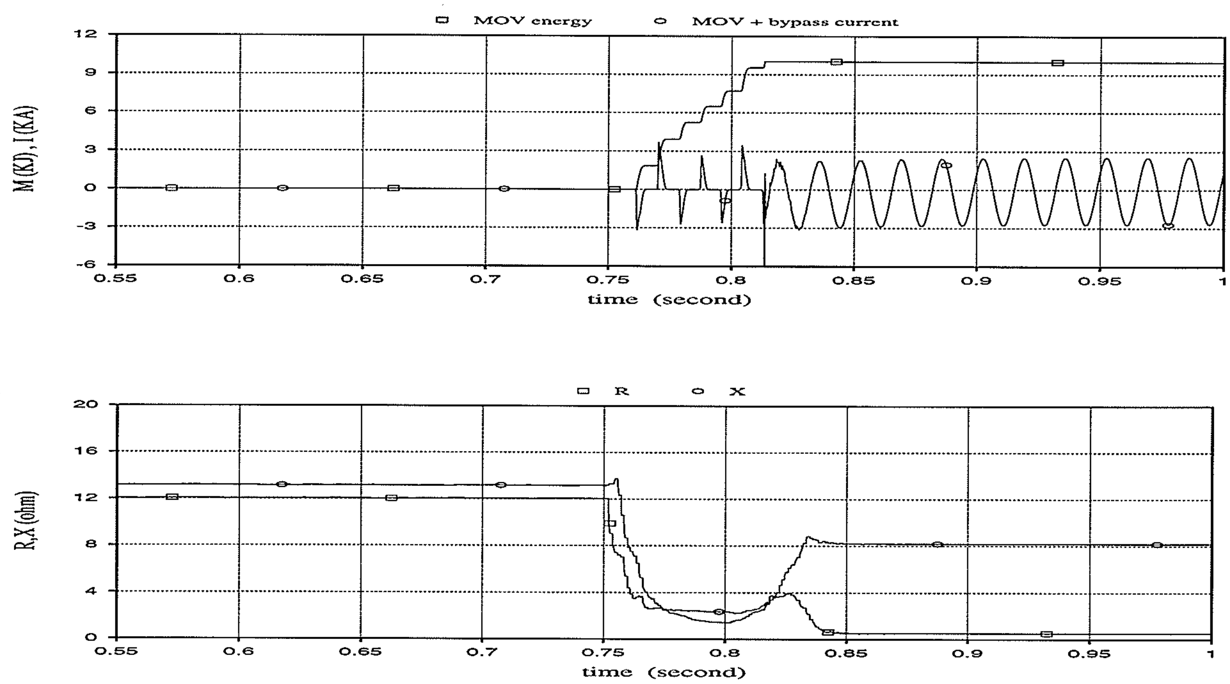


Fig. 3.3.3.1 High fault current causing both MOV and by–pass switch to operate

The above scenarios occur only for end–compensated lines with the relay PT on the bus side and for mid–compensated lines. For end–compensated lines, the fault always occurs beyond the capacitor. Some adaptive algorithms, which use the fault current level to obtain the equivalent impedance for the capacitor and the conducting MOV, and then adjust the relay operating zone settings, may be used to solve this problem. Also, the time when the by–pass switch will be operated could also be estimated by using the fault current level [8].

However, the problem is complicated for mid–compensated lines, because for either a fault close to the bus where relay is located, or a fault occurring beyond the capacitor but close to the capacitor, the fault current will be the same. Thus the above mentioned adaptive algorithm may not be used.

The above analysis has discussed the problems of protecting a series compensated line using impedance relays in detail. As the analysis shows, some of these problems are easy to solve, while others are difficult to solve. In general, when all of the above factors are considered, the mid–compensated lines have more severe problems in using impedance relays to protect them, while end–compensated line have less problems of using impedance relays.

CHAPTER 4:
DORSEY–FORBES–CHISAGO TRANSMISSION LINE

§ 4–1 Introduction

The Dorsey–Forbes–Chisago line is a 500 kV inter–system tie–line between Manitoba Hydro System and Northern States Power System. The line was upgraded in 1993 with the inclusion of series compensation on both sections of the line to increase the transmission capacity.

Prior to the installation of the series capacitors, on site relay transient tests [10] and off–line studies [1] were conducted between 1991 and 1992 to investigate the performance of existing relay systems protecting the line. The existing line relay system consists of two independent systems [10]. The on site tests and the off–line studies both show that the settings of these relays should be adjusted to partially overcome the problems caused by the series compensation [10]. As the analysis of the previous chapter shows, adjusting impedance relay settings can not completely solve all the problems caused by the series compensation, and further studies are required. This project is the continuation of the previous studies. Its purpose is to develop an adaptive digital MHO relay algorithm to improve the relay performance on the series–compensated Dorsey–Forbes–Chisago line.

In this chapter, the details about the Dorsey–Forbes–Chisago line before and after series compensation will be presented. The modelling of the line on PSCAD/EMTDC is also presented. An adaptive digital APT relay model was also built up and simulated with this line model to test the adaptive relaying algorithms. The adaptive relay algorithm and the simulation results of the relay will be presented in the later chapters.

§ 4–2 Dorsey–Forbes–Chisago line before compensation

As shown in Fig. 4.2.1, The Dorsey–Forbes–Chisago line consists of two sections: the north line section running from the Dorsey converter station in southern Manitoba to the Forbes substation in Minnesota, a distance of 537 km; the south line section running from the Forbes substation to the Chisago substation, a distance of 220 km.

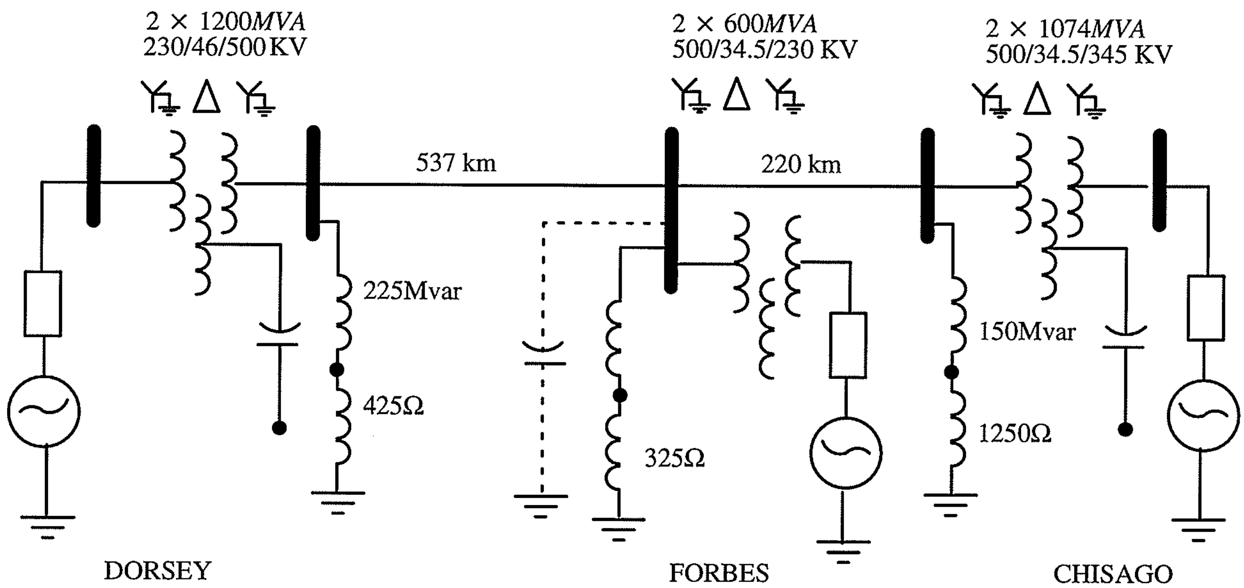


Fig. 4.2.1 Dorsey–Forbes–Chisago transmission line without series capacitor

The shunt inductors are installed at the Dorsey, Forbes and Chisago substations to improve the voltage profile. Without the series compensation, the line impedance including the shunt reactor is $182.6\angle 87.3^0$ (ohm) for the north section and $76.4\angle 87.2^0$ (ohm) for the south section. For the purpose of increasing the exchange of power capacity between the two systems, series compensation was chosen.

§ 4–3 Dorsey–Forbes–Chisago line after compensation

The series capacitors were installed in both sections of the Dorsey–Forbes–Chisago line. In the Dorsey–Forbes section, the series capacitors were installed at the location close to the middle point of the line section (225 km from Dorsey). While in the Forbes–Chisago section, the series capacitor was installed at the busbar of the Chisago substation. The Dorsey–Forbes–Chisago line after the compensation is shown in Fig. 4.3.1 (The dotted capacitor connection at Forbes represents the future inclusion of an SVC at this busbar).

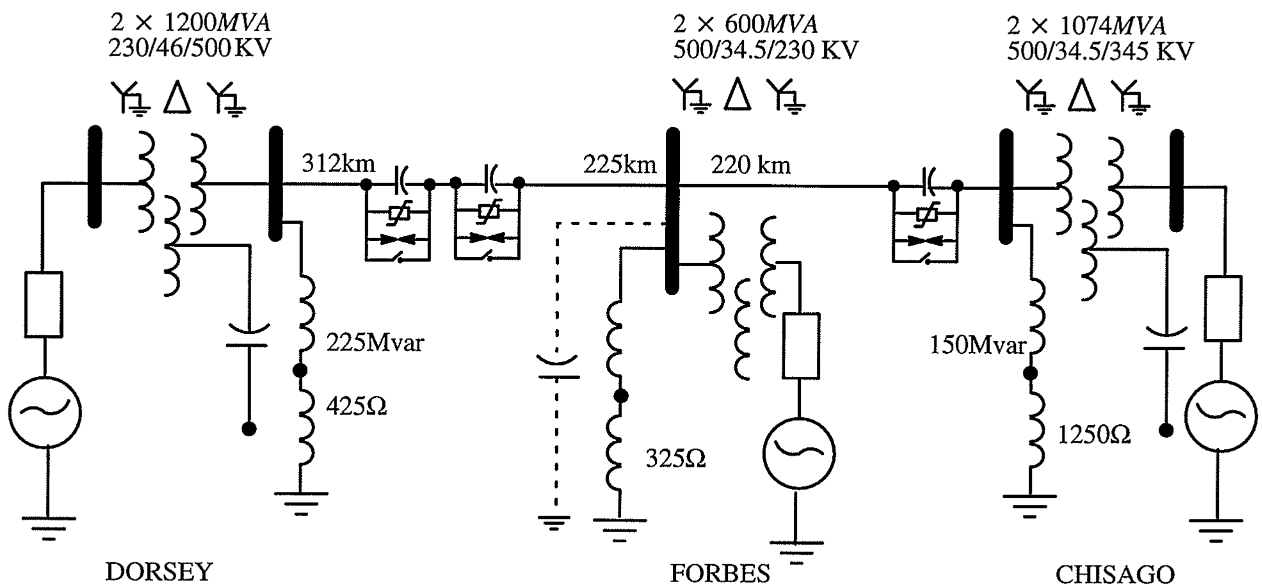


Fig. 4.3.1 Dorsey–Forbes–Chisago transmission line with series capacitors

As shown in Fig. 4.3.1, the Dorsey–Forbes section has two series capacitors thus having two compensation degrees. When one series capacitor ($c = 63.9\ \mu f$) is in–service, the compensation degree is 25%, which reduces the equivalent line impedance to 155.5 (ohm). When both capacitors ($c = 31.95\ \mu f$) are in–service, the compensation degree becomes 50%, reducing the equivalent line impedance to 114 (ohm).

[**N.B.** The position of the series compensation on the north line section does not correspond to the actual location. This does not alter any of the results and conclusions in this thesis but the system analyzed does not correspond exactly to the actual Dorsey–Forbes–Chisago system.]

The Forbes–Chisago section has only one series capacitor ($c = 63.9\ \mu f$) with the compensation degree of 50%. The equivalent line impedance is reduced to 33.91 (ohm) when this series capacitor is in–service.

§ 4–4 Simulating Dorsey–Forbes–Chisago line on PSCAD/EMTDC

The development of an adaptive digital relay algorithm was mainly conducted on an advanced digital Electromagnetic Transients simulation software PSCAD/EMTDC [15], developed by the Manitoba HVDC research Center. The Dorsey–Forbes–Chisago line is modelled in detail using the actual line parameters on the EMTDC (for Draft diagram, refer to Appendix A).

Other than the transmission line modelling, both Manitoba Hydro System and Northern States Power System are represented by the Thevinin equivalent EMFs and impedances. Shunt reactors are also modelled in the system, as can be seen from the draft diagram in Appendix A.

The series capacitors are modelled with their protection circuits. The protection of the series capacitors consists of an MOV, a spark gap and a by–pass switch (refer to Fig. 2.5.4 in Chapter 2). The thermal protection of the MOV is also modelled.

The same line had been modelled on EMTDC version 2, which did not have sufficient graphical interface support, in the previous studies conducted in [1]. The current EMTDC version 3 is supported by a powerful graphical interface program PSCAD, on which a system can be modelled graphically. In the previous studies, the validity of the simulation results had been confirmed by comparing the simulation results with the actual field tests [10]. When the line model was re–built on EMTDC version 3, the simulation results were compared with the results of previous studies, showing consistent results. A digital impedance relay is then implemented and modelled on EMTDC along with this system.

As the subsystem 1 of the Draft diagram (Appendix A) shows, CTs and PTs, sampling circuit, filters, FFT calculations, impedance calculations and relay zone comparison circuits of an impedance relay with quadrilateral characteristics are all modelled. The problems of the conventional impedance relay and the adaptive algorithms were investigated with extensive use of this relay model. The details of the adaptive algorithm will be discussed in the following chapters.

CHAPTER 5:

FAULT LOCATION DETECTION: BASIC THEORY

§ 5–1 Introduction

As the analysis in Chapter 3 shows, the protection of a mid–compensated transmission line with a high degree of compensation has three major problems: (1) part of the line section close to the series capacitor is covered only by zone 1 of the relay at one end of the line; (2) part of the line section is not covered by relay zone 1 for relays at both ends when capacitor is out–of–service, (3) the conduction of the MOV during internal faults causes the initially in–zone impedance locus to go out of zone when a fault occurs behind the capacitor. These problems can not be solved by utilizing conventional impedance relays. The end–compensated line has similar problems but its problems could be solved by carefully selecting the PT location and obtaining the capacitor in–service status to change the relay settings accordingly.

An adaptive impedance relay concept is developed in this thesis work to solve the above problems related to the protection of mid–compensated lines. In this chapter, the differing fault induced transients as affected by fault location, the detection of fault induced transient components, and the concept of adaptive impedance relaying for mid–compensated lines will be presented.

§ 5–2 Fault induced transients as affected by fault locations

When a fault occurs in a transmission line, the voltages and currents in the system will contain the following three components: a fundamental frequency pre–fault load component, fundamental frequency fault component and fault induced transient components. The fault induced transient components will decay with time. For a long–distance transmission line without series compensation, the fault induced transients typically contain one exponentially decaying DC component and an infinite number of exponentially decaying oscillating components with frequencies higher than the system fundamental frequency.

When a line is series–compensated, the fault induced transient components seen by a relay differ, depending upon the relative locations of the fault, the capacitor and the relay. A three–phase fault is used to illustrate the difference, which allows a single line diagram (Fig. 5.2.1) to be used since this is a symmetrical fault.

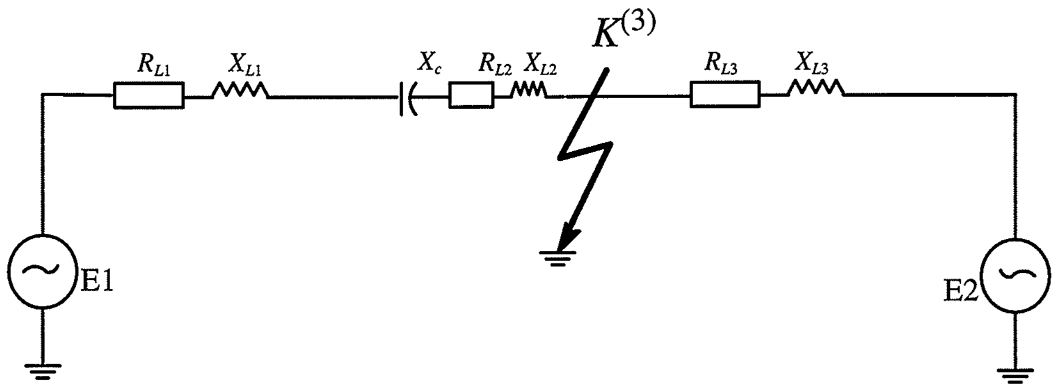


Fig. 5.2.1 A three phase fault in a mid–compensation line

As can be seen from Fig. 5.2.1, the fault divides the system into two parts: one contains a series capacitor and one does not. In the part which does not contain the series capacitor, the fault induced transient components are the same as that in a transmission line without series compensation. However, in the part containing the series capacitor, a decaying sub–synchronous oscillating component will occur instead of the decaying DC component while both contain other high frequency fault induced transient components. The difference between them can be seen clearly from Fig. 5.2.2 and Fig. 5.2.3.

Thus if high frequency fault induced transient components are not considered (assuming they have been filtered out by the relay), a relay located in the part of the line without a series capacitor will see only a decaying DC transient component, but a relay in the part containing the series capacitor will see a decaying sub–synchronous oscillating component. This can be used to adaptively adjust the setting of a digital impedance relay. The adaptive impedance relaying algorithm will be discussed in the next section.

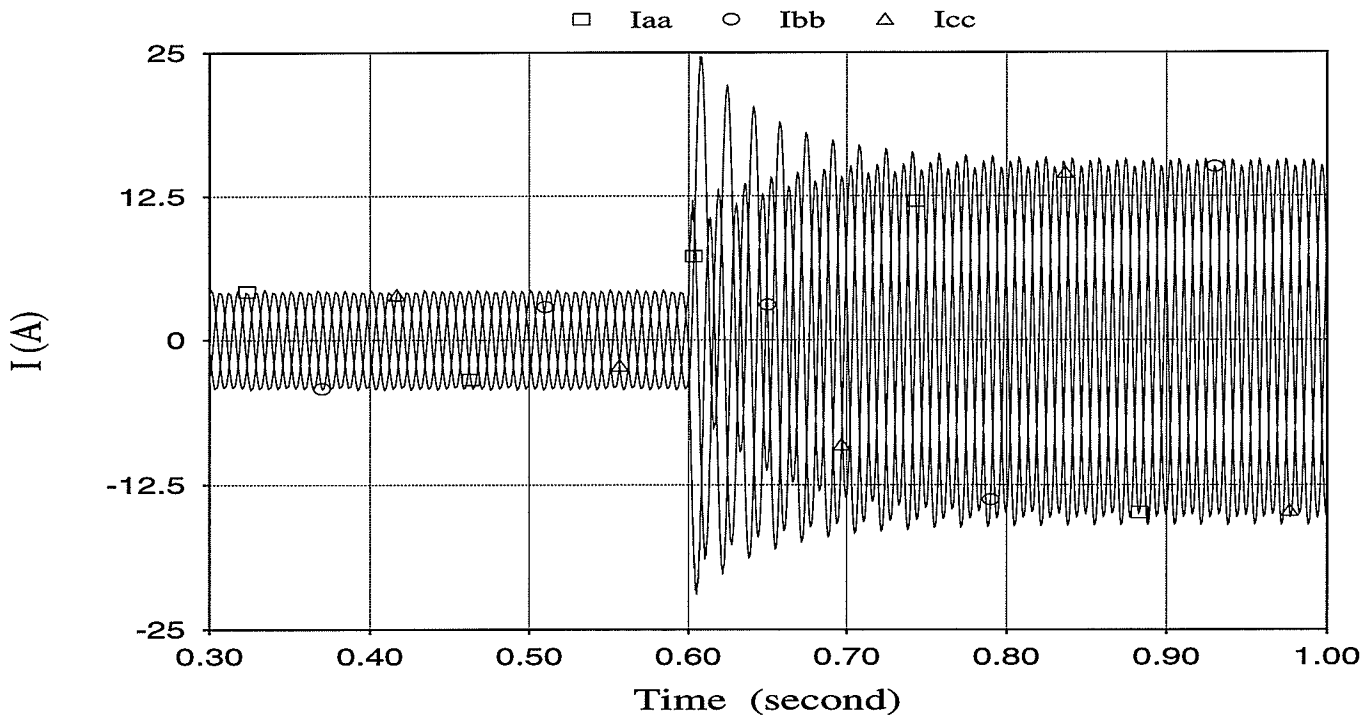


Fig. 5.2.2 Fault current in the part without series capacitor

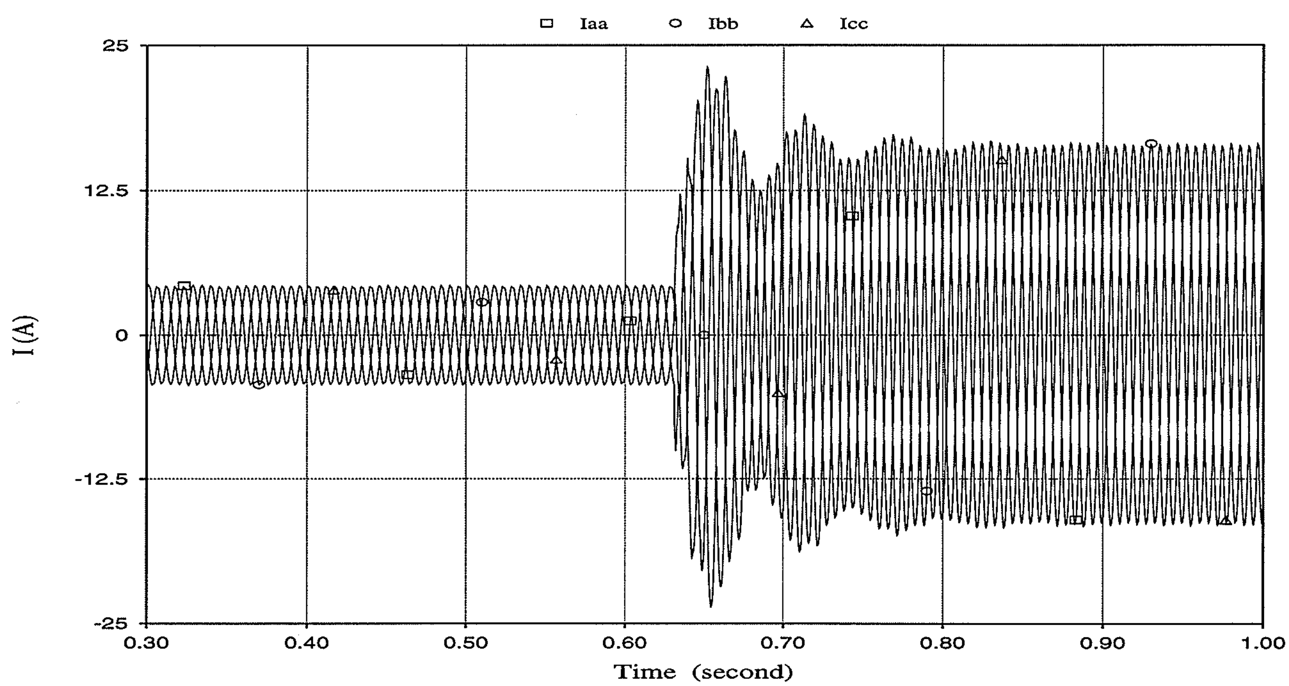


Fig. 5.2.3 Fault current in the part containing the series capacitor

§ 5–3 Adaptive digital impedance relay concept and algorithms

From a relay's point of view, the difference discussed in the section 5–2 can be summarized as follows: (1) when a series capacitor is out–of–service, the decaying DC transient component will be seen by the relay; (2) if a fault has occurred in front of the series capacitor when it is in–service, the decaying DC transient component will be seen by the relay; (3) if a fault has occurred behind the series capacitor when it is in–service, a decaying sub–synchronous transient component will be seen by the relay. Here the high frequency fault induced transient components are assumed to have been filtered out by the relay and only forward faults are considered assuming that the relay has no difficulties in determining fault directions.

The main difference between a DC component and a sub–synchronous component is that the DC component never changes its polarity while the sub–synchronous component's polarity changes constantly. Thus if the DC decaying transient component or the sub–synchronous decaying transient component can be obtained from the fault voltage or current, an adaptive impedance relaying algorithm as shown in Fig. 5.3.1 can be used to solve the problems of a mid–compensated line.

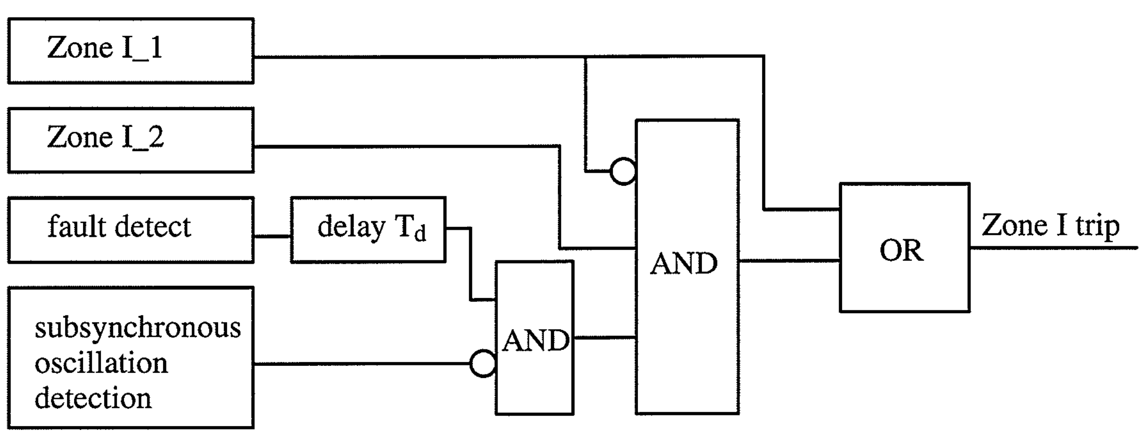


Fig. 5.3.1 Adaptive impedance relaying algorithm for mid–compensated line

The algorithm uses two settings for its zone 1 protection as shown in Fig. 5.3.2. One is the capacitor in–service setting based on the line impedance $Z_l - j\,X_c$

$$Z_{setting1} = 0.8 \times (Z_l - jX_c) \qquad (5.1)$$

and another one is the capacitor out–of–service setting based on the line impedance Z_l.

$$Z_{setting2} = 0.8 \times Z_l \qquad (5.2)$$

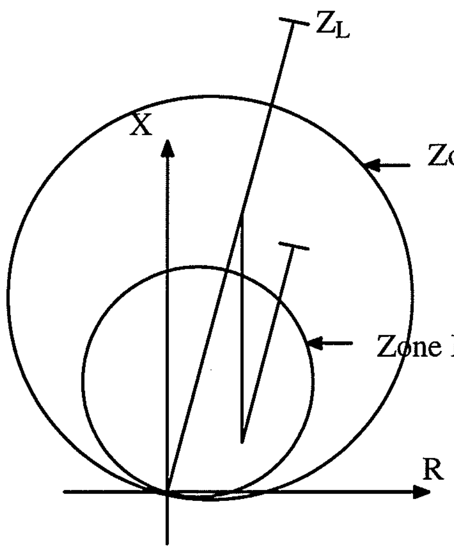


Fig.5.3.2 Two setting zone 1 adaptive impedance relaying

As the logic in Fig. 5.3.1 shows, any fault with a fault impedance that falls within the $Z_{setting1}$ area will generate an immediate trip signal, which allows for fast fault clearance for close in faults. For faults with a fault impedance that falls outside the $Z_{setting1}$ but within the $Z_{setting2}$, the generation of a trip signal is delayed for a short time. If within the time delay Td (2 or 3 cycles) delay, a sub–synchronous transient component is detected, the generation of a trip signal will be blocked, because the presence of a sub–synchronous transient component indicates that the series capacitor is in–service and the fault has occurred beyond the capacitor from the relay point of view. As can be seen from Fig. 5.3.2, a fault occurring on an adjacent line section could also have its impedance fall within the $Z_{setting2}$ area. Blocking the generation of a trip signal can prevent possible overreach tripping under this condition.

With the above adaptive algorithm, the two main problems related to the impedance relaying for a mid–compensated line are solved. When a fault has occurred close to the series capacitor and its fault impedance falls outside of $Z_{setting1}$, a trip signal still can be generated after the specified time delay, since no sub–synchronous transient component is contained in the voltages and currents. When the series capacitor is out–of–service and a fault has occurred within $Z_{setting2}$ but outside $Z_{setting1}$ area, again no sub–synchronous transient component will be detected but now a trip signal will be generated after the specified time delay.

Though the above adaptive impedance relaying algorithm introduces a certain time delay for tripping on faults occurring within the $Z_{setting2}$ area but outside the $Z_{setting1}$ area, it still offers shorter fault clearance time than the one solely relying on the communication links or a Zone 2 timer.

As can be seen from the Fig. 5.3.1, the correct detection of the sub–synchronous transient component and determining the time of delay are critical for the above described adaptive impedance relaying algorithm. These two issues will be discussed in the next section.

§ 5–4 Detection of a fault induced DC or sub–synchronous transient component

There exists certain difficulties in detecting a fault induced DC or sub–synchronous transient component. First, their magnitudes are not constant and decay with time. Second, the initial magnitudes, the decay time constant for both the DC and sub–synchronous components and the frequency of sub–synchronous component are affected by the fault location, fault type, system condition and the voltage phase angle when the fault occurs.

Normal filtering techniques, such as low–pass filtering, are not adequate for detecting a fault induced DC or sub–synchronous transient component. A fault induced sub–synchronous transient component in a series compensation system has a frequency close to the nominal system frequency (60 Hz in North America). The frequency of a sub–synchronous transient component is determined by the total inductance between the fault location, the source ground, and the capacitance of the series capacitors (refer to Fig. 5.2.1). It could be in the 20 to 40 Hz range.

To cut off the fundamental component as well as the above 60 Hz harmonic components and at the same time to preserve sub–synchronous transient component by a low–pass filter proved to be too difficult to accomplish. It would require the filter to have a very steep cutoff frequency characteristic, as the two frequencies are very close to each other, and the magnitude of the fundamental component is usually larger than that of the sub–synchronous transient component.

With such difficulties, a different approach is used in this study. The technique is based on the Fourier series expansion. The author has extended the Fourier series expansion method by introducing a time variable in the Fourier expansion coefficients calculation. The technique is explained in detail as follows:

For a periodical signal f(t) with a period of T, it can be represented by a Fourier series as

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left(a_n \sin n\omega t + b_n \cos n\omega t\right) \qquad (5.3)$$

where $\omega = \frac{2\pi}{T}$, and

$$a_0 = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\, dt \qquad (5.4)$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\, \sin n\omega t\, dt \qquad (5.5)$$

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\, \cos n\omega t\, dt, \qquad (5.6)$$

The functions of sin(nωt) and cos(nωt) are orthogonal when integrated over the range of –T/2 to T/2. That is for $n = 1, 2, 3 \ldots$

$$\int_{-T/2}^{T/2} (1 \times \sin n\omega t)\, dt = 0, \quad \text{and} \quad \int_{-T/2}^{T/2} (1 \times \cos n\omega t)\, dt = 0 \tag{5.7}$$

and for $n,\ m = 1, 2, 3 \ldots$

$$\int_{-T/2}^{T/2} (\sin n\omega t \times \cos m\omega t)\, dt = 0 \tag{5.8}$$

as well as for $n \neq m$

$$\int_{-T/2}^{T/2} (\sin n\omega t \times \sin m\omega t)\, dt = 0 \qquad \int_{-T/2}^{T/2} (\cos n\omega t \times \cos m\omega t)\, dt = 0 \tag{5.9}$$

but $$\int_{-T/2}^{T/2} 1 \times 1\, dt \neq 0 \tag{5.10}$$

and for $n = m$

$$\int_{-T/2}^{T/2} (\sin n\omega t \times \sin m\omega t)\, dt \neq 0 \qquad \int_{-T/2}^{T/2} (\cos n\omega t \times \cos m\omega t)\, dt \neq 0 \tag{5.11}$$

Thus if f(t) contains only a finite number of harmonics, its Fourier series expansion will contain only a finite number of components corresponding to each of the harmonics. The $a_0/2$ in the Fourier expansion of f(t) corresponds to the magnitude of the DC component contained in f(t), and $c_n = \sqrt{(a_n^2 + b_n^2)}$ is equal to the magnitude of the corresponding "nth" harmonic component.

The expansion described above is the normal Fourier series expansion. The normal Fourier series expansion can be extended to include a time variable in the integrations of its coefficient calculations. The extended Fourier series expansion's coefficient calculation is now integrated from (t–T) to t, which corresponds to the real situation where the Fourier series expansion is always done on the latest one cycle window of data of the input signal. With such an extension, the coefficient calculation equations now become

$$a_0(t) = \frac{2}{T}\int_{t-T}^{t} f(\tau)\ d\tau \qquad (5.12)$$

$$a_n(t) = \frac{2}{T}\int_{t-T}^{t} f(\tau)\ sin(n\omega\tau)\ d\tau \qquad (5.13)$$

$$b_n(t) = \frac{2}{T}\int_{t-T}^{t} f(\tau)\ cos(m\omega\tau)\ d\tau \qquad (5.14)$$

It is easy to prove that the orthorgonality of functions sin(nωt) and cos(nωt) still holds for this changed integration range. That is

for $n = 1, 2, 3 \ldots$

$$\int_{t-T}^{t} (\ 1 \times \sin n\omega\tau\ )\ d\tau = 0, \qquad \text{and} \qquad \int_{t-T}^{t} (\ 1 \times \cos n\omega\tau\ )\ d\tau = 0 \qquad (5.15)$$

and for $n,\ m = 1, 2, 3 \ldots$

$$\int_{t-T}^{t} (\ \sin n\omega\tau \times \cos m\omega\tau\ )\ d\tau = 0 \qquad (5.16)$$

as well as for $n \neq m$

$$\int_{t-T}^{t} (\ \sin n\omega\tau \times \sin m\omega\tau\ )\ d\tau = 0, \qquad \int_{t-T}^{t} (\ \cos n\omega\tau \times \cos m\omega\tau\ )\ d\tau = 0 \qquad (5.17)$$

but $$\int_{t-T}^{t} (\ 1 \times 1\ )\ d\tau \neq 0$$

and for $n = m$

$$\int_{t-T}^{t} (\ \sin n\omega\tau \times \sin m\omega\tau\ )\ d\tau \neq 0, \qquad \int_{t-T}^{t} (\ \cos n\omega\tau \times \cos m\omega\tau\ )\ d\tau \neq 0 \qquad (5.18)$$

When the magnitudes of all harmonic components and the DC component are constant, the magnitudes of these harmonics and the DC component calculated from the above equations will be kept constant when the window of acquired data changes as time t changes.

However, when a decaying DC component or a decaying sub–synchronous component is contained in the input signal f(t), the magnitude of the DC component calculated from the above extended Fourier series expansion equation will display a very useful property. To simplify the following analysis, f(t) is assumed to contain only a finite number of harmonic components and a DC or sub–synchronous component with a constant magnitude. When a DC component is contained in the f(t), i.e.

$$f(t) = A_0 + \sum_{n=1}^{N}\left(\sqrt{a_n^2 + b_n^2} \times \sin(n\omega\tau + \alpha)\right)$$

the $a_0(t)$ will be

$$a_0(t) = \frac{2}{T}\int_{t-T}^{t}\left(A_0 + \sum_{n=1}^{N}\left(\sqrt{a_n^2 + b_n^2} \times sin(n\omega\tau + \alpha)\right)\right) d\tau = \frac{2}{T}\int_{t-T}^{t} A_o \, d\tau = 2 \times A_0 \qquad (5.19)$$

as

$$\frac{2}{T}\int_{t-T}^{t}\sum_{n=1}^{N}\left(\sqrt{a_n^2 + b_n^2} \times \sin(n\omega\tau + \alpha)\right) d\tau = 0 \qquad (5.20)$$

When a sub–synchronous component is contained in the f(t), i.e.

$$f(t) = A_0 \sin(\Omega\tau + \alpha) + \sum_{n=1}^{N}\left(\sqrt{a_n^2 + b_n^2} \times \sin(n\omega\tau + \alpha)\right)$$

where $\Omega = \frac{2\pi}{T_1}$ and $T_1 > T$, the $a_0(t)$ will be

$$a_0(t) = \frac{2}{T}\int_{t-T}^{t}\left(A_0 \sin(\Omega\tau + \alpha) + \sum_{n=1}^{N} \sqrt{a_n^2 + b_n^2} \times sin(n\omega\tau + \alpha) \right) d\tau$$

$$= \frac{2}{T}\int_{t-T}^{t} A_0 \sin (\Omega\tau + \alpha) \, d\tau = \frac{2T_1A_0}{T\pi}\sin\left(\frac{T\pi}{T_1}\right)\sin\left(\Omega t + \alpha - \frac{T\pi}{T_1}\right) \qquad (5.21)$$

as

$$\frac{2}{T}\int_{t-T}^{t}\sum_{n=1}^{N}\left(\sqrt{a_n^2 + b_n^2} \times sin(n\omega\tau + \alpha) \right) d\tau = 0 \qquad (5.22)$$

Equation (5.19) shows that when a DC component is contained in the f(t), $a_0(t)$ is a DC signal and does not change its polarity as time t passes.

However, the a_o becomes a function of t, $a_0(t)$, when a sub–synchronous component is contained in f(t) (equation 5.21). The frequency of $a_0(t)$ is the same as the frequency of the sub–synchronous component contained in the f(t), but its magnitude is different from the one contained in the f(t).

Fig. 5.4.1 shows the original sub–synchronous component contained in the f(t), and also the $a_0(t)$ waveforms. The DC component is not shown in the graph as it is only a straight line.

The above results show that a sub–synchronous component or a DC component could be detected by performing the integration continuously on a one cycle data window of the input signal along the time t axis. This would be difficult to implement using an analog circuit, but can be done very easily in a digital relay system.

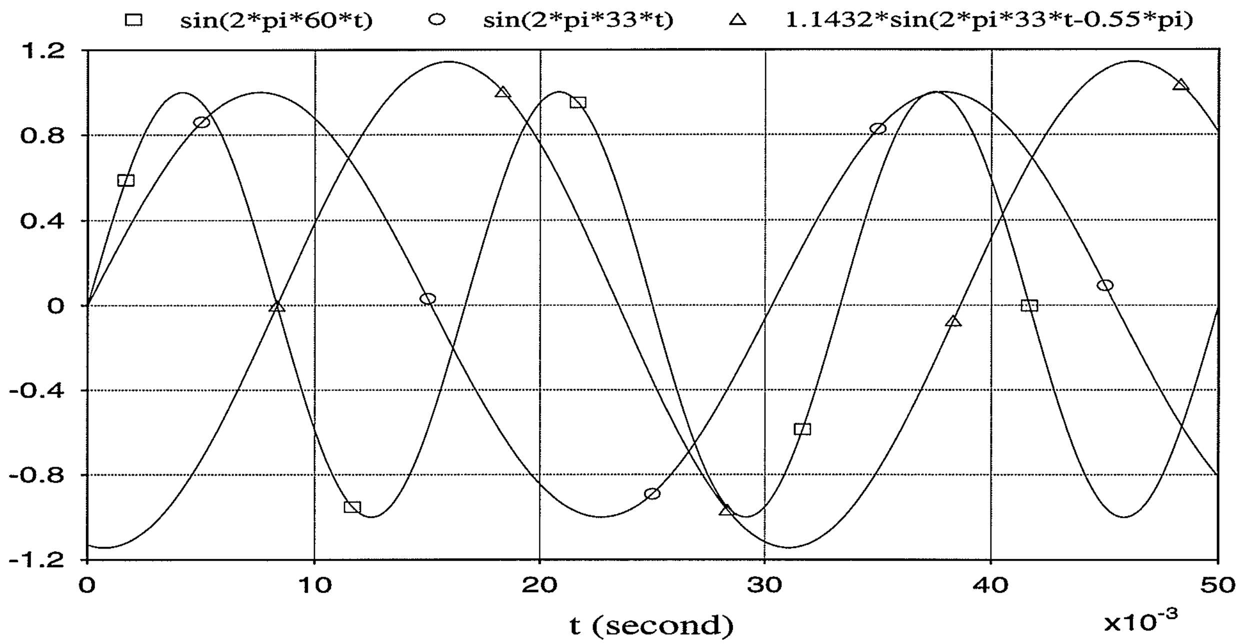


Fig. 5.4.1 $a_o(t)$ waveform and the original sub–synchronous component

As shown below, the above integration of $a_0(t)$ can be approximated by the simple summation of the sampled data taken in a one cycle period. That is:

$$\int_{T_1}^{T_2} f(t)\; dt \approx \left(\frac{T_2 - T_1}{N}\right)\sum_{n=0}^{N-1} f\left(T_1 + n \times \frac{T_2 - T_1}{N}\right) \tag{5.23}$$

The time difference between two consecutive integrations should be small enough to obtain a smooth $a_0(t)$ waveform (Fig. 5.4.2). As shown in Fig. 5.4.2, with a sampling rate greater than 8 points/cycle, a smooth waveform can be obtained (Note that it is assumed that the integrations are conducted every time a new sample is obtained). In the Fig.5.4.2, the 32, 16 and 8 point/cycle curves are offset vertically by a small DC value to allow the comparison between curves.

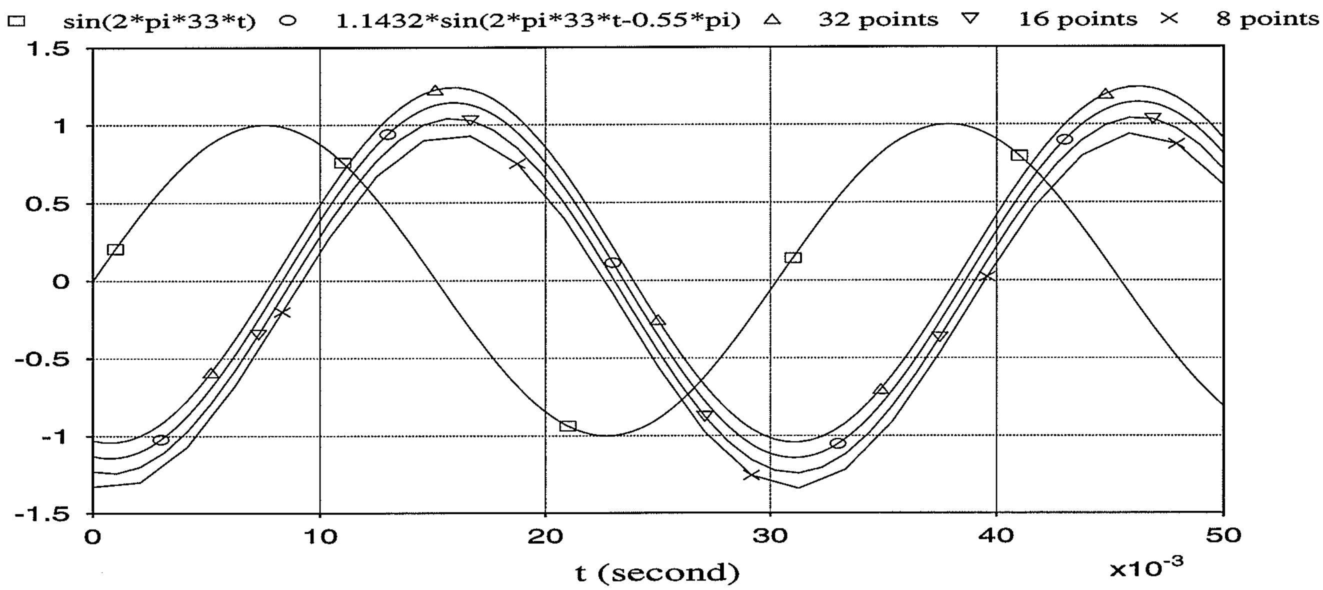


Fig. 5.4.2 Different sampling rate effect

When an oscillating $a_0(t)$ or a DC a_0 waveform is obtained, the detection of the sub–synchronous component becomes simple. The number of polarity changes are counted in the specified time delay period after a fault. If it is greater than 2 (from a pre–fault containing no DC components to containing a DC component may cause one polarity change), a sub–synchronous component is contained in the fault voltage or current.

As to whether to perform the above integrations on voltage or current signals, it is felt that current signal is more appropriate, as a fault normally causes the transmission line's current to increase, and the current level will be the same anywhere along the line. For voltage signals, their magnitudes are affected by the fault location and it will become zero if the fault has occurred close to the busbar.

The time delay in the adaptive impedance relay algorithm discussed in the previous section determines the response time of the $Z_{setting2}$ zone 1. It should be chosen so that for the lowest sub–synchronous frequency, it still gives sufficient time for the sub–synchronous detection part to detect the sub–synchronous component correctly. The lowest sub–synchronous frequency occurs when the fault has occurred at the far end of the $Z_{setting2}$ zone 1 area and the capacitor is in service. Since the polarity of $a_0(t)$ will change twice in half a cycle of $a_0(t)$, the time delay will be a little more than one fundamental cycle if the lowest frequency of $a_0(t)$ is 30 Hz (a typical value). Such a time delay still offers an acceptable fast relaying compared to relying completely on the communication channel.

The above DC or sub–synchronous component detection method is stable as it does not use instantaneous data but rather the integration of one cycle's data. Random noise or data error will have little effect on the results of the algorithm.

The above analysis shows that it is feasible to use a sub–synchronous component detection method to adaptively select the relay settings. However, the above analysis is based on a three–phase fault without fault resistance. When different types of faults, fault resistances, and the action of MOVs and by–pass breakers in the series capacitor protection circuit are considered, the above method should be adjusted. These will be discussed in the next chapter.

CHAPTER 6:

FAULT LOCATION DETECTION: OTHER PROBLEMS

§ 6–1 Introduction

The analysis in the previous chapter shows the feasibility of using a sub–synchronous transient component detection method to adaptively adjust the impedance relay settings. However, the analysis in the previous chapter only considers a three–phase fault without fault resistance. For the application of this adaptive algorithm, its feasibility in other situations must be analyzed.

There are two main situations that need to be considered: non–three–phase fault situations and faults with fault resistances. Besides these two main situations, the action of the series capacitor's protection circuit during an internal fault changes the impedance seen by the relay, thus should be analyzed. The Dorsey–Forbes line has two different capacitor in–service situations: two capacitor banks in–service, and one capacitor bank in–service situation. This will affect the performance of the adaptive algorithm. In the following sections, the effects of these situations on the adaptive impedance relay algorithm will be analyzed and the necessary modifications to the adaptive algorithm will be discussed.

It is obvious that there will be no sub–synchronous transient component when the capacitor is out–of–service, thus the adaptive impedance relay algorithm should operate correctly regardless of the fault type and the fault resistance. Also there will be no impedance changes caused by the MOV action during the fault. Thus the following analyses will focus on the performance of the adaptive algorithm when the capacitor is in–service.

To simplify the analysis, the diagrams shown in the following sections will show only a decaying DC or sub–synchronous transient component (which will be referred to as "transient component" in the following sections) in most cases. These transient components are obtained from the original phase current waveforms based on the Extended Fourier expansion method (equation

5.12 to 5.22 from page 49 to page 51). The original voltage and current waveforms will be shown when it is necessary.

§ 6–2 Dealing with non–three–phase faults

Non–three–phase fault situations include single phase–to–ground fault and phase–to–phase fault situations. Fig. 6.2.1 and Fig. 6.2.2 show the transient components of all three phases for the single line–to–ground faults. The fault in Fig. 6.2.1 has occurred at T1 bus of Dorsey–Forbes line section (in front of the capacitor from the relay point of view), and the fault in Fig. 6.2.2 has occurred at T3 of the same line section (beyond the capacitor from the relay point of view). The T1 and T3 bus locations are shown in the PSCAD/EMTDC draft diagram of Appendix A. The current value shown in Fig. 6.2.1, Fig. 6.2.2 and the other later figures are the current value on the secondary side of the CT (Appendix A).

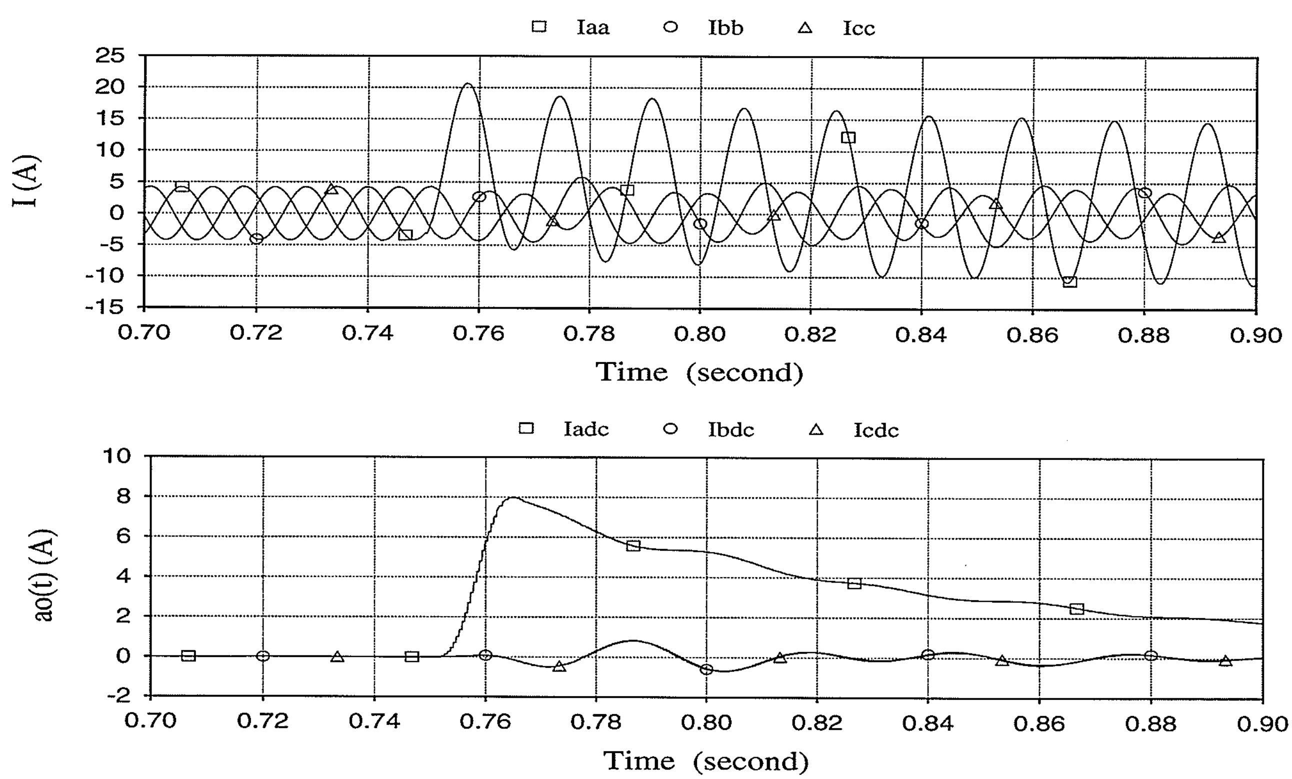


Fig. 6.2.1 Transient components of a phase A to ground fault in front of the capacitor

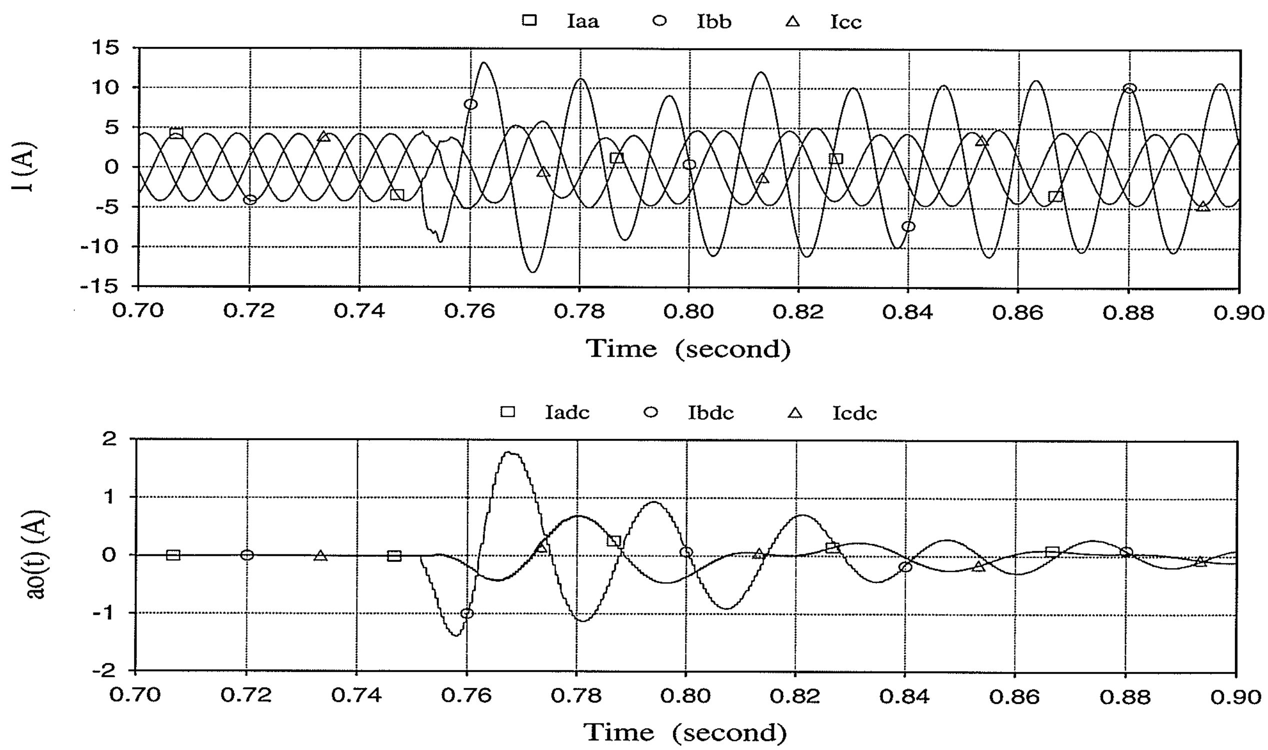


Fig. 6.2.2 Transient components of a phase B to ground fault beyond the capacitor

As can be seen from the diagram, the transient component of the faulted phase shows the same characteristic as in a three phase fault, thus the adaptive impedance relay algorithm still can be used for the relays on the faulted phase(s) in this condition. For unfaulted phases, sub–synchronous transient components appeared in both cases. Thus for unfaulted phases, both faults will be seen by the adaptive algorithm as a fault behind the capacitor, and the $Z_{setting1}$ zone 1 with a small operating area will be used. As relays in unfaulted phases do not operate under these conditions, this does not become a problem for the adaptive algorithm.

Similar conclusion can be obtained for a phase–to–phase fault. Fig. 6.2.3 and Fig. 6.2.4 show the transient components of all three phases for the phase–to–phase faults. The fault in Fig. 6.2.3 has occurred at T1 (in front of the capacitor), and the fault in Fig. 6.2.4 has occurred at T3 (behind the capacitor).

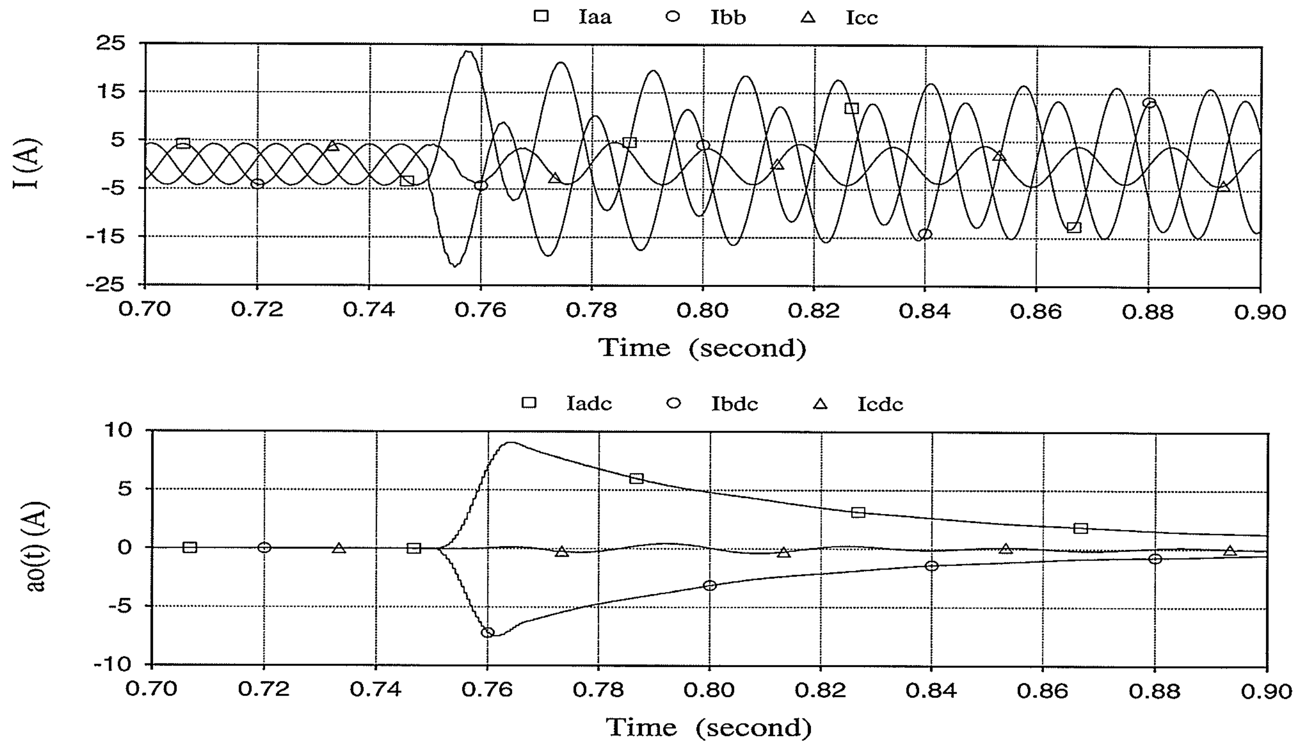


Fig. 6.2.3 Transient components in a phase–to–phase fault in front of the capacitor

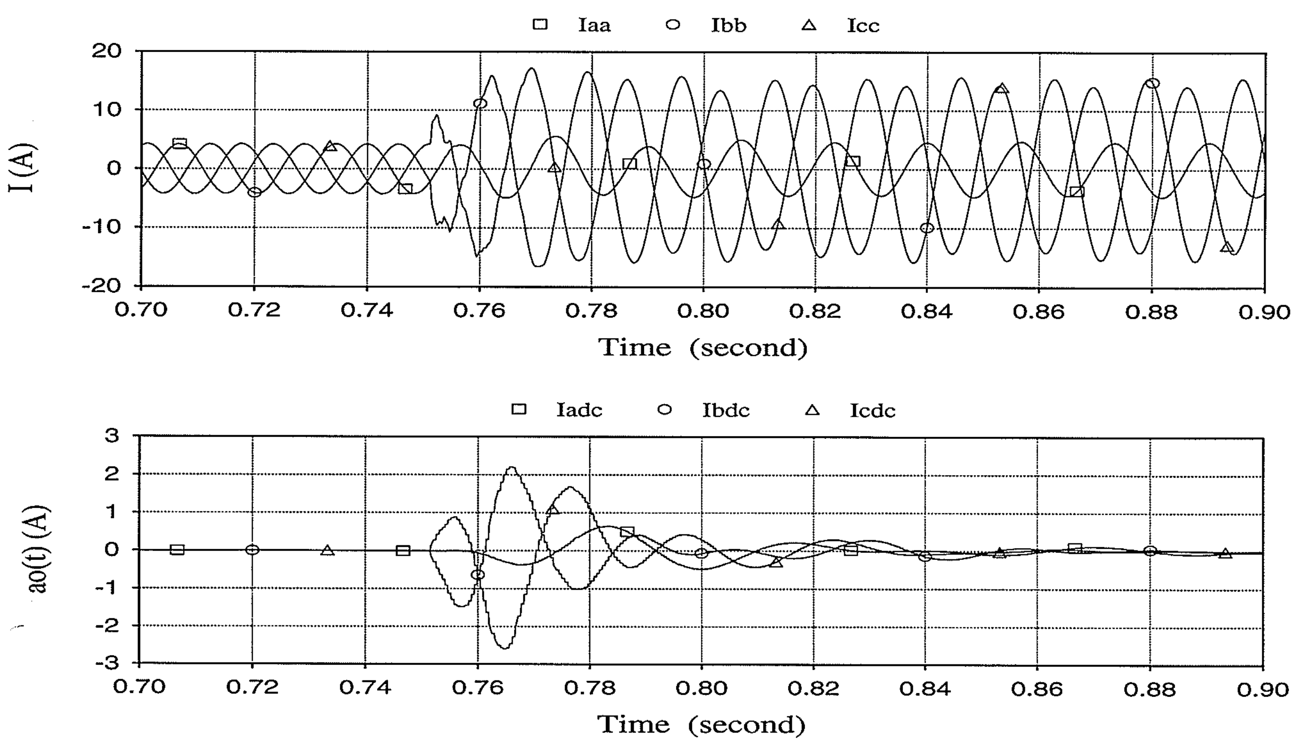


Fig. 6.2.4 Transient components in a phase–to–phase fault behind the capacitor

In conclusion, non–three–phase fault situations do not pose major problems for the adaptive impedance relay algorithm.

§ 6–3 Considering the effects of fault resistances

To be simple, a three–phase fault with fault resistance will be considered. Similar results can be obtained for non–three–phase fault situations. Fig. 6.3.1 and Fig. 6.3.2 show the transient component of one phase for the three phase faults occurring in front of and behind the capacitor respectively. The fault resistance is 20 (ohm) per phase.

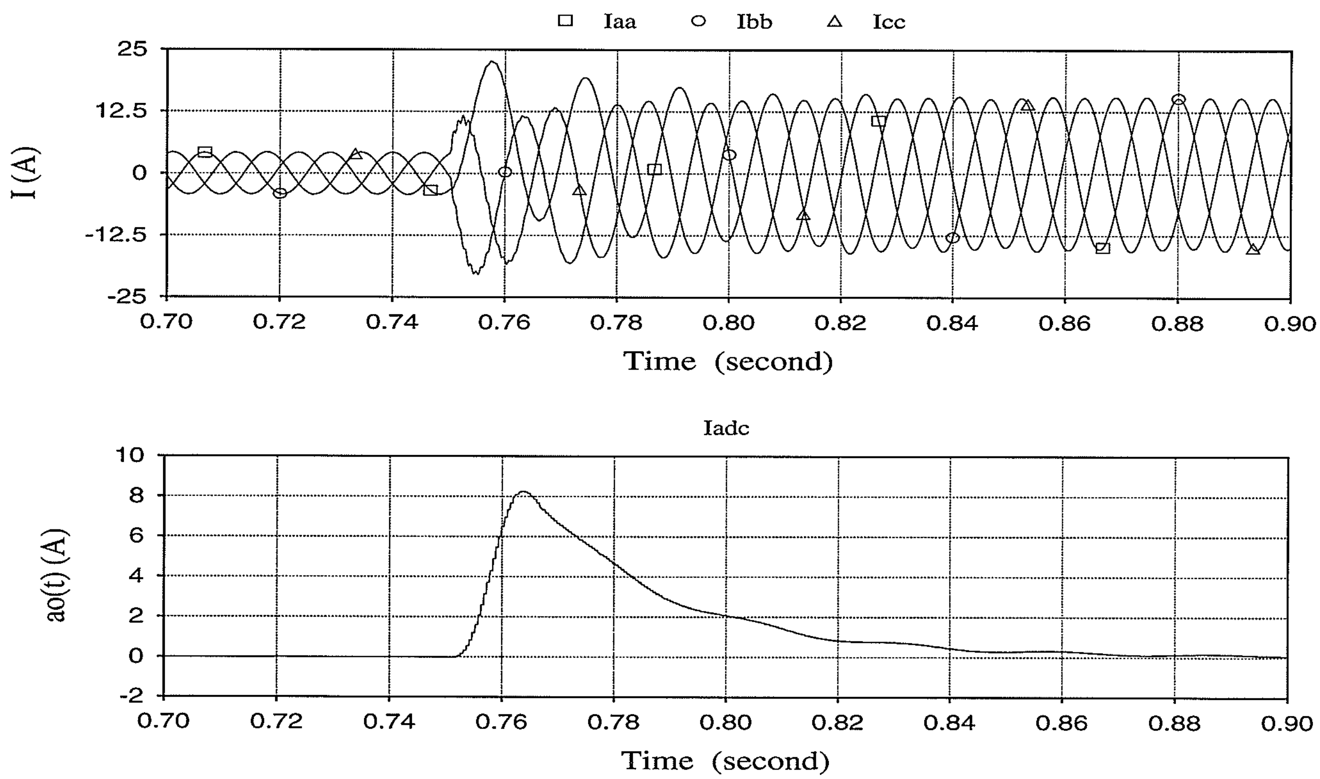


Fig. 6.3.1 One phase transient component in a three–phase fault with fault resistance (occurring in front of the capacitor)

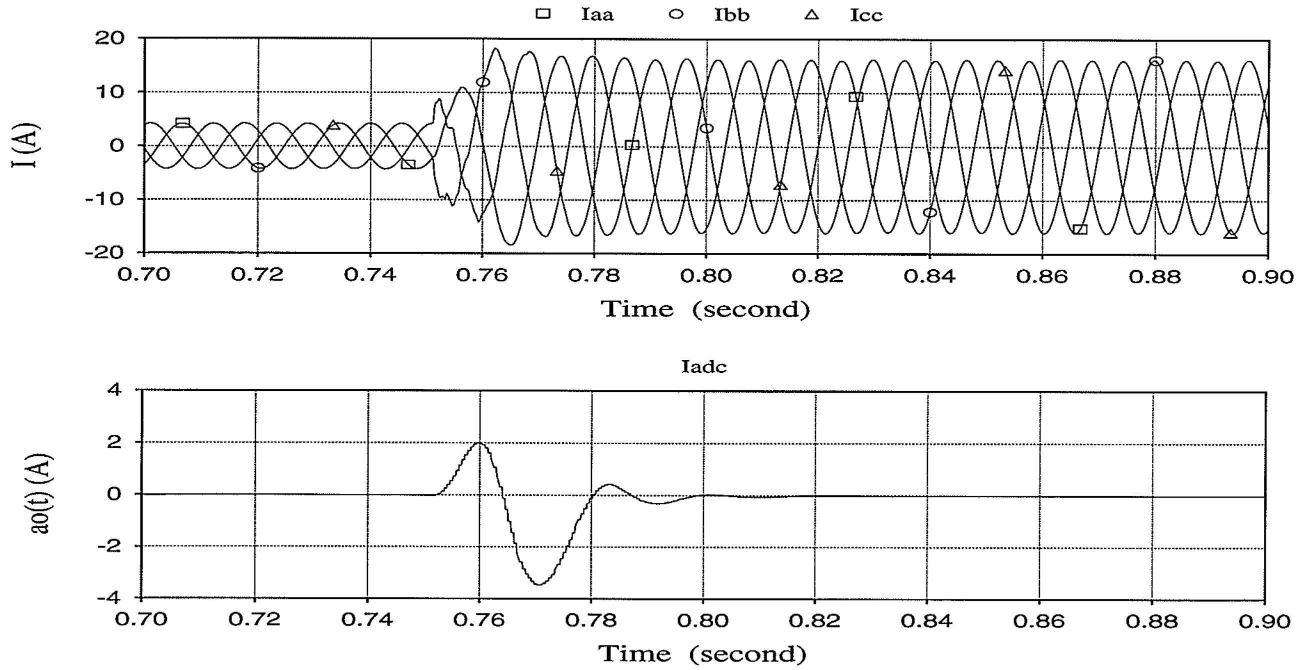


Fig. 6.3.2 One phase transient component in a three–phase fault with fault resistance (occurring behind the capacitor)

As can be seen from the diagrams, the transient components in these two cases contain both decaying DC and sub–synchronous components. However, for the fault occurring in front of the capacitor, the DC component is dominant while for the fault occurring behind the capacitor, the sub–synchronous component becomes dominant. The result can be easily understood with the assistance of a single line diagram shown in Fig. 6.3.3.

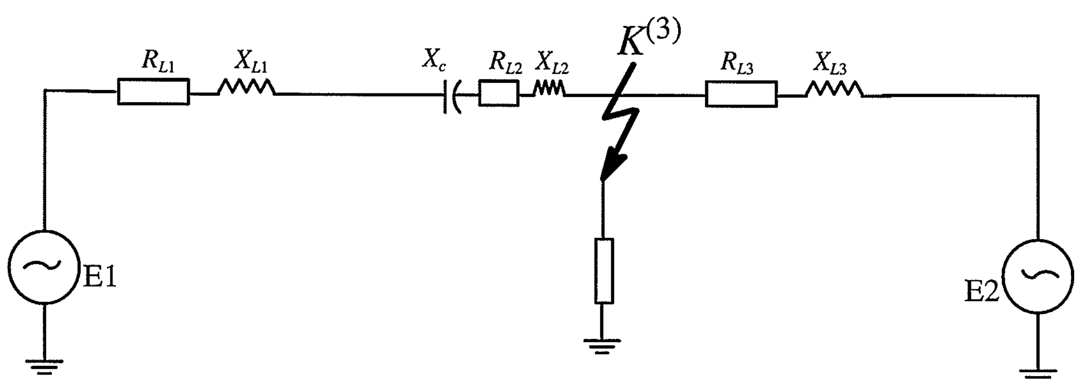


Fig. 6.3.3 Single line diagram for a three phase fault with fault resistance

When there is no fault resistance, the transient current components (DC in the part without the capacitor and sub–synchronous in the part containing the capacitor) flow through the fault location and do not appear in the current of another part. When a fault has occurred with a fault resistance, a linear superposition method should be used to analyze the distribution of the transient component.

For the decaying DC transient component, the impedance of the line part containing the capacitor and the fault resistance becomes an equivalent impedance connected with the part not containing the capacitor. Therefore a portion of the decaying DC transient current component will flow in the part containing the capacitor (the DC component can flow through capacitor due to the fact that it is not a pure DC component and it is superimposed onto the fundamental component). Depending on the value of the fault resistance and the fault location, the percentage of the decaying DC transient current component is different. The lower the fault resistance is, the smaller will be the DC component in the part containing the capacitor. The same results can also be obtained for the sub–synchronous transient component.

A dominant decaying sub–synchronous component containing a small decaying DC component does not affect the polarity changes, thus will not affect the adaptive algorithm under this condition. However, when a dominant decaying DC component contains a small decaying sub–synchronous component, there is a danger that after the DC component decays to a certain level the combined signal will start to change polarities. This will lead to a false result being obtained. To avoid such false detection, another time delay after a fault, which is used to allow the generation of the sub–synchronous component detected signal, should be limited. It should be a little longer than the specified time delay in the adaptive logic shown in Fig. 5.3.1. After the allowed time delay, the signal should be locked to ensure the correct selection of settings by the adaptive algorithm.

With the above modification, the adaptive impedance relay algorithm can work properly under the existence of fault resistance. This has also been verified for all fault conditions including the non–three–phase fault conditions.

§ 6–4 Taking the series capacitor's protection into account

It has been mentioned before that the MOV protection circuit is the most widely used protection circuit for series capacitors. As will be discussed below, the equivalent impedance of a series capacitor protected by the MOV protection circuit changes during a fault when the MOV operates. The impedance change pattern of an MOV protected series capacitor is more complicated than a spark–gap protected one. Thus in the following analysis, the effect of the MOV protection circuit operation during a fault on the adaptive algorithm will be the main focus.

For a spark–gap protected series capacitor, it has only two impedance values during a fault, i.e. Xc when spark gap is not fired and 0 when it is fired. While for an MOV–protected series capacitor, its equivalent impedance during a fault is affected by the fault current level and the action of the MOV protection circuit.

There are several possible scenarios when the action of an MOV protection circuit is considered. The possible scenarios are: (1) The fault current is below the MOV conducting level. (2) The fault current is above the MOV conducting level but the energy absorption capacity will not be reached before the sub–synchronous transient component is detected (polarity changes twice or more before the spark–gap fires due to the energy absorption limit of the MOV being reached). (3) The fault current is very high so that the energy absorption capacity of the MOV is reached before the sub–synchronous transient component can be detected in the specified time delay.

When the adaptive algorithm is applied to these conditions directly, the first scenario and the third scenario do not impose major problems. For the first scenario, the sub–synchronous component can be detected correctly. Thus the correct $Z_{setting1}$, which is the correct setting under this condition, will be selected. For the third scenario, the firing of spark gap and the consequent close of by–pass switch eventually by–passed the capacitor. As the sub–synchronous component is not detected within the specified time delay, the $Z_{setting2}$ is correctly selected. This, too, will result in a correct operation of the relay.

However, the scenario (2) does cause some problems for the adaptive impedance relay algorithm. Due to the conduction of the MOV, the equivalent impedance of the capacitor and the MOV now changes corresponding to the fault current level. The net effect of MOV conduction is that the –jXc of the series capacitor now becomes R'–jXc' (Xc' < Xc) [6]. As the sub–synchronous component can be correctly detected in this case, the $Z_{setting1}$ zone 1 will be selected. The reduction of Xc will cause the impedance seen by the relay to increase for faults occurring at the location close to the end of $Z_{setting1}$ zone 1. This may result in the impedance seen by the relay falling out of $Z_{setting1}$ operating zone. As $Z_{setting2}$ is not selected, these faults will not be tripped until Zone 2 or other protection systems operate.

Besides, when the energy absorption capacity of the MOV is reached in scenario (2), the spark gap will fire and the by–pass switch will be closed. This results in the fault impedance changing to the value without series compensation. Due to the fault resistance effect as discussed before, the sub–synchronous component detection is only allowed for a short period and then the result is locked. The $Z_{setting2}$ will not be selected for this case either.

According to the analysis in [6], the equivalent impedance of the capacitor with a conducting MOV is predictable by using the fault current level. The energy accumulation of the MOV can also be calculated based on the MOV characteristic and the fault current. With these two facts, another adaptive strategy (the second adaptive algorithm) can be used to solve the above problem.

When the fault current level exceeds the MOV conduction level and the sub–synchronous component is detected, the measured impedance will be subtracted by a value of R'–j(Xc–Xc') which corresponds to the change of Xc caused by the MOV conduction at this fault current level. This will bring the impedance seen by the relay to fall within $Z_{setting1}$ operating area. The energy accumulation of the MOV is also simulated in the relay based on the MOV characteristic and the fault current level. When the energy absorption capacity of the MOV is exceeded, $Z_{setting2}$ will be selected. This will allow the relay to trip the fault correctly.

The application of this adaptive algorithm is possible only if the fault location relative to the capacitor is known, as a fault in front of the capacitor and a fault behind the capacitor could have the same fault current level. With the assistance of the sub–synchronous transient component detection, this adaptive algorithm can be used to solve the above problems.

In summary, by applying the second adaptive algorithm, the problems of the primary adaptive algorithm caused by the MOV protection circuit can be solved.

§ 6–5 Considering different capacitor in–service situations

For the Dorsey–Forbes line section, there is a different problem as the capacitor banks could be only one bank in–service or both banks in–service. Theoretically, the adaptive algorithm should use two capacitor in–service settings corresponding to the two capacitor in–service conditions. Some efforts were made to use the frequency difference of the sub–synchronous transient components under these two conditions to distinguish these different capacitor in–service conditions. However, the results show that it is difficult to use the frequency difference for this purpose due to the following facts.

The frequency of the sub–synchronous transient component is determined by the total line inductance from the fault location to the source ground and the series capacitor's capacitance. For any one of these two capacitor in–service conditions, the frequency of the sub–synchronous transient component varies in a wide range when the fault location varies. The simulation results show that the possible frequency range for one capacitor in–service condition is 27–44 Hz and for two capacitor banks in–service is 18–32 Hz . Due to the over–lap of these two frequency ranges, it is difficult to use the frequency difference to distinguish these two conditions.

One alternative is to use the two capacitor banks in–service setting to cover both situations. The one capacitor in–service setting can not be used to cover both conditions, as it may cause an over–reach problem when two capacitor banks are in service (Fig. 6.5.1). As can be seen from the

Fig. 6.5.1, when the two capacitor in–service setting is used while only one capacitor bank is in service, the line is still fully covered by the relay zone 1 protection which can be analyzed as follows.

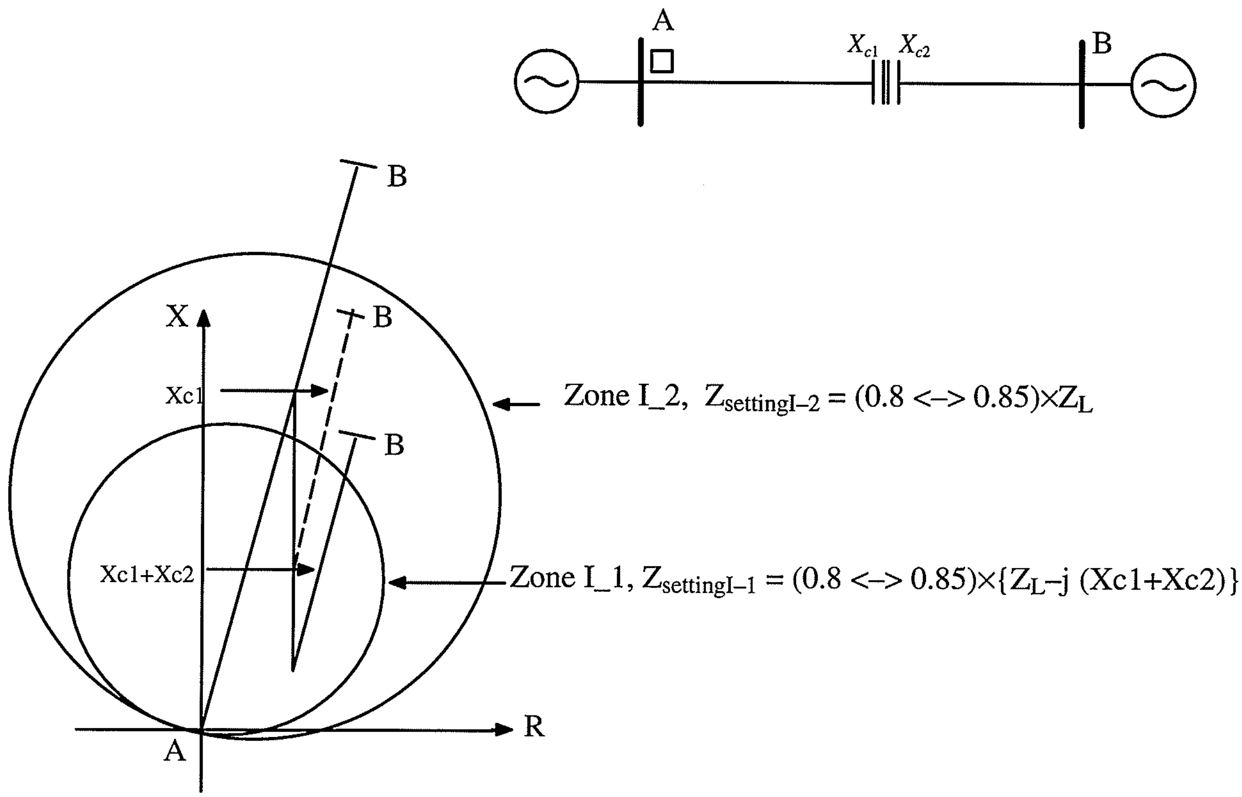


Fig. 6.5.1 Two zone 1 settings for two capacitor in–service conditions

For the relay on one end of the line, it fully covers the line section between the relay and the capacitors, since the relay sees decaying DC transient components for faults occurred on this section. The adaptive algorithm will select $Z_{settingI-2}$ to correctly trip the faults. For faults occurring at the line section between the capacitor and the remote end of the line, the relay has a reduced coverage compared to the two capacitor banks in–service condition, as can be seen from the Fig. 6.5.1.

Thus the result of using two capacitor banks in–service setting for both conditions is that it still has the line fully covered by the zone 1 protection, but fewer faults will be tripped by the relay zone 1 on both ends. This is because the overlap area of both relay's zone 1 is reduced compared to two capacitor banks in–service condition.

CHAPTER 7:

IMPLEMENTATION OF ADAPTIVE IMPEDANCE RELAY ALGORITHM

§ 7–1 Introduction

The original goal of this study is to develop an adaptive impedance relay algorithm for the protection of series compensated lines connecting Manitoba Hydro System and Northern States Power System. If possible, it is also desirable to implement and test the developed adaptive algorithm on the current APT (Advanced Power Technology) relay platform.

The APT relay platform is a universal relay development platform for different protection projects of Manitoba Hydro. The hardware of this platform consists of a PC motherboard, a plug–in DSP (Digital Signal Processor) board and specially designed input/output interface circuit boards. The design of APT relay software structure aims to isolate the most difficult hardware control programming part, which is programmed in Assembly language, from the relay algorithms programming part using "C" high level language. This is to facilitate other graduate students and relay engineers using this platform to implement their relay algorithms.

Due to the complexity of the problems associated with the protection of a series compensated line using impedance relays, most of the time was spent on the clarification of the problems, off–line simulations and development of the adaptive digital impedance relay algorithm presented in the previous chapters. The developed adaptive impedance relay algorithm has been successfully implemented and tested on PSCAD/EMTDC software. However, it has not yet been implemented on the APT relay platform due to some programming difficulties. In this chapter, the implementation of this adaptive algorithm on PSCAD/EMTDC is presented in detail. The difficulties, as well as the considerations and the steps for implementing this adaptive algorithm onto the APT relay platform, will be discussed later in this chapter.

§ 7–2 Adaptive algorithm implemented on PSCAD/EMTDC

The advancement of digital Electromagnetic Transient simulation software has changed the traditional relay development, design and test procedure considerably. In the past, when a new relay algorithm was developed, a prototype had to be built and tested on a Transient Network Analyzer (TNA). The purpose of building a prototype and conducting tests on a TNA was to find the problems in the new algorithm in an actual implementation and to fix these problems before going to field tests. A prototype usually needs to go through several rounds of prototype modification and testing on a TNA to implement the new algorithms properly. This process is usually a very time consuming, costly and strenuous process. After the prototype has passed the TNA test, it will be installed to undergo field testing. The final production and application of the relay using the new algorithm comes after the prototype has successfully passed the required field test.

With the help of digital Electromagnetic Transient simulation software, a new approach can be used. The relay algorithm can be tested off–line directly on the digital simulation software and the major implementation problems can be fixed before building the first prototype. This approach greatly reduces the time, effort and cost in the development of a relay prototype implementing a new algorithm. This cost–efficient approach was adopted in the development of the adaptive impedance relay algorithm in this project.

In this study, first the Dorsey–Forbes–Chisago transmission system model with the series capacitors was constructed on PSCAD/EMTDC version 3. The model was built up on EMTDC version 2 in the previous studies [1] and the validity of the model was compared with the staged fault tests of the Dorsey–Forbes–Chisago line [1]. The same system model was successfully transferred onto the current PSCAD/EMTDC (version 3) and the same results were obtained. This model was then used extensively to generate different fault waveforms under different fault conditions for investigating the protection problems of the Dorsey–Forbes–Chisago transmission system and testing the adaptive impedance relay model also implemented on the PSCAD/EMTDC software.

The adaptive impedance relay model constructed on PSCAD/EMTDC is basically a normal digital three–phase impedance relay model with the quadrilateral characteristics. The relay model closely resembles an actual digital impedance relay which has been implemented on the current APT relay platform. It includes three phase impedance elements and three ground impedance elements. Each impedance element has two zones to cover the faults occurring on the line. The model samples the line current and bus voltage waveforms generated by the Dorsey–Forbes–Chisago transmission system model, and performs the necessary digital processing and relay functions on the sampled data in the same way as in an actual relay. The relay model uses the quadrilateral characteristic which is necessary because the MHO circle characteristic will have a reduced fault resistance coverage when the capacitor in–service setting is used. The relay model was placed at the Dorsey substation of the Dorsey–Forbes line section.

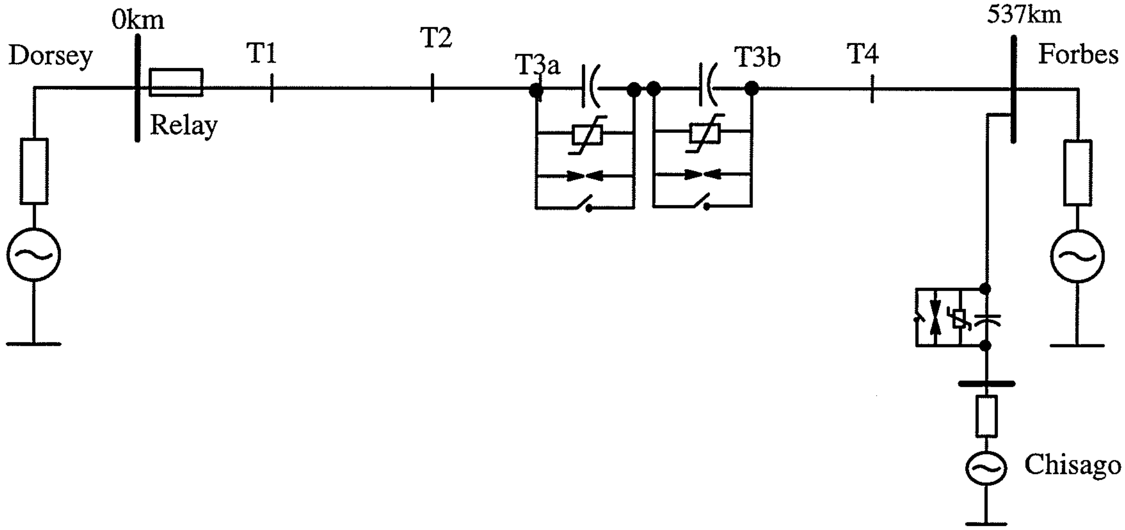
As can be seen from the printout of sub–system 1 in Appendix A, the relay model consists of the following blocks: sampling block, high–pass filter block, FFT calculation block, impedance calculation block and relay characteristic block. These functional blocks are the same as the actual relay functional blocks which have already been implemented in the APT relay platform. The high–pass filter of the relay is used to filter out the sub–synchronous transient component to reduce the spiral in measured fault impedance locus.

The adaptive algorithm was then implemented to work along with the APT relay model. First the transient component extracting block was used. It takes the sampled data which is the output of the sampling block directly as its input. A one cycle integration of the sampled data is performed for each phase once a new sample is obtained. A polarity change counter starts to count the number of polarity changes in the transient component after a fault has occurred. The polarity changes are only counted in a specified time period (1.5 cycle) after the fault.

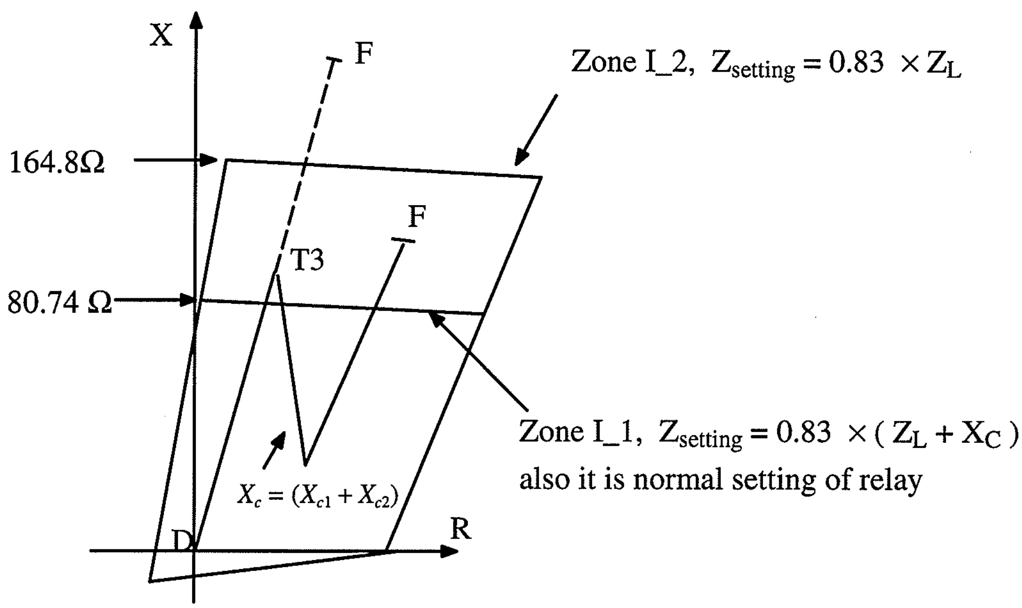
The polarity change counting block has two output signals, one "NoC" signal for "DC transient component detected" and one "HasC" signal for "sub–synchronous transient component detected". Both signals are "low" at normal system operating conditions. When the number of polarity changes in the specified time period is less than two, the "NoC" signal become high after the specified time delay, while the "HasC" signal remains low. If the number of polarity changes is equal to or greater than two in the specified time period, the "HasC" signal will become high immediately after the polarity changes twice and the "NoC" signal will be forced to remain low. After the specified time delay, both signals will be locked to prevent false detection after the transient components decays. The provision of two signals facilitates the implementation of an adaptive setting selection logic design. With two signals available, the adaptive setting selection logic part is free to use whichever is convenient of these two signals.

The locked signals are then used to adaptively select the correct relay settings. When the "NoC" signal is high and the "HasC" signal is low, the $Z_{setting1}$ is used. When the "NoC" signal is low and the "HasC" signal is high, the $Z_{setting2}$ will be used. When the $Z_{setting2}$ is used, the measured impedance value is adjusted to cancel the effect of MOV conduction when the fault current is high. The adjustment of the measured impedance is according to the fault current level. The adaptive relay setting selection logic and the adaptive measured impedance adjustment part are implemented in the relay algorithm part, where the measured impedance and the relay settings are compared in a normal impedance relay.

The adaptive relay algorithm implemented on PSCAD/EMTDC has been tested under different fault conditions. Some of the results have been shown in the previous chapters. The results show that under different fault conditions the transient components can be correctly extracted, thus the correct settings will be selected. Fig.7.2.1 shows the test line from Dorsey to Forbes to Chisago and the impedance relay settings for this line with two series capacitors. The following table compares the relay performance for using or not using the adaptive algorithm under different fault conditions:



a . Dorsey–Forbes–Chisago 500kv line
(see note on page 39)



b. 2–setting Zone I impedance relay characteristic for two capacitor inservice

Fig. 7.2.1 The impedance relay setting for line with two series capacitors

Table 7.2.1. Adaptive algorithm is not used (capacitors **in**–service; fault resistance 0 to 50 Ω)

location	phase to ground	phase to phase to ground	phase to phase
T1	tripping	tripping	tripping
T2	tripping	tripping	tripping
T3a	no tripping	no tripping	no tripping
T3b	tripping	tripping	tripping
T4	tripping	tripping	tripping

Table 7.2.2. Adaptive algorithm is used (capacitors **in**–service; fault resistance 0 to 50 Ω)

location	phase to ground	phase to phase to ground	phase to phase
T1	tripping	tripping	tripping
T2	tripping	tripping	tripping
T3a	tripping	tripping	tripping
T3b	tripping	tripping	tripping
T4	tripping	tripping	tripping

Table 7.2.3. Adaptive algorithm is not used (capacitors **out**–service; fault resistance 0 to 50 Ω)

location	phase to ground	phase to phase to ground	phase to phase
T1	tripping	tripping	tripping
T2	tripping	tripping	tripping
T3a	no tripping	no tripping	no tripping
T3b	no tripping	no tripping	no tripping
T4	no tripping	no tripping	no tripping

Table 7.2.4. Adaptive algorithm is used (capacitors **out**–service; fault resistance 0 to 50 Ω)

location	phase to ground	phase to phase to ground	phase to phase
T1	tripping	tripping	tripping
T2	tripping	tripping	tripping
T3a	tripping	tripping	tripping
T3b	tripping	tripping	tripping
T4	tripping	tripping	tripping

The experience in developing this new adaptive relay has proved the efficiency of using Electromagnetic Transient simulation software in relay algorithm development. The algorithm had undergone several major changes to make it operate correctly. Were the old method used, several prototypes would have had to be built to obtain the same results.

§ 7–3 Implementing adaptive algorithm on APT relay platform

The implementation of the adaptive algorithm developed in this study on the current APT relay platform encountered some difficulties due to the present APT relay software structure. The design of the APT relay software structure emphasizes the isolation of relay algorithms programming part from the hardware control programming part. A relay program typically consists of the main relay algorithm part and the hardware control part. In the current APT relay platform, the relay algorithms are designed to be programmed using the high level language "C", while the hardware control part is pre–programmed in Assembly language. The purpose of such isolation is to ease the difficulties of programming different relay algorithms on the APT relay platform for the relay engineers and researchers.

As the result of such isolation, the entry point to start relay algorithm programming is sample data buffers containing a full cycle of sampled data of each of the input signals. Either DFT or FFT subroutines can be called to process the buffered data into the phasors of these input signals. Further relay algorithm calculations and functions can be programmed to use these phasors, such as an impedance relay. The sampling of input signals is independent of the relay algorithm part. The sampling data as stored in the buffers is not intended to relate to the time sequence but to keep the correct phase relationships between these signals. The relay algorithm programmer does not know how this sampled data in the buffer is related to the exact time sequence. Moreover, the relay algorithm program part is not executed in a fixed time period, i.e., it can be executed in less than one sampling interval or in more sampling intervals, depending on the tasks it needs to accomplish.

The difficulties in implementing the adaptive algorithm are mainly associated with the transient component detection part. As has been shown in the previous chapters, to extract a smooth transient component by the extended Fourier expansion method, the one cycle integration should be done every time a new sample is obtained. To achieve the fastest response time in the polarity change count, it is also necessary to test for polarity changes every time a new sample is obtained. The current APT relay software structure does not allow both of these requirements to be fulfilled. Though one cycle integration of sampled data can be done on the sampled data stored in the buffers, there is no guarantee that such an integration can be performed every time a new sample is obtained.

To implement the adaptive impedance relay algorithm properly, the current APT relay software structure should be modified. Besides the access to sampled data in the buffers, it should also allow relay algorithm programmers to access the sampled data on a time basis, i.e., the sampled data can be accessed every time a new sample is obtained and the data can be accessed in the correct order with respect to the time. This requirement is very important, as some time–domain relay algorithms do not use the DFT or FFT phasors but use the sampled data directly.

When the software structure of the APT relay platform is modified, the implementation of the adaptive impedance relay algorithm becomes simple. It can be implemented by integrating one cycle sampled data and checking for polarity changes every time a new sample is obtained. The one cycle integration can be improved by utilizing an iterating method, i.e., when a new sample is obtained, it is added to the previous integration result and at the same time the oldest sample in the previous integration result is subtracted from it. The output of transient component extraction program could use the same output signals "HasC" and "NoC" as in the relay model on the PSCAD/EMTDC.

The rest of the implementation of the adaptive algorithm is straight forward. The transient component signals are used to select the correct Zone 1 setting in a specified time delay after the fault occurs. The adaptive algorithm starts its time delay whenever a fault starting algorithm, such as a ΔI algorithm, detected a fault. When the sub–synchronous transient component is detected, the measured impedance should be adjusted accordingly, based on the fault current level used to offset the effect of MOV conduction. The time delay and the adjustment of impedance is system dependent. The calculation of time delay has been presented in previous chapters, and the impedance–current relationship due to MOV conduction can be obtained using the method presented in reference [6].

CHAPTER 8:

ACHIEVEMENTS AND CONCLUSIONS

The main achievements of this research are in the following two areas:

1) The problems associated with the protection, especially the fast relaying, of a series compensated line are clarified and analyzed in this thesis.

2) An adaptive impedance relay algorithm for fast relaying of a mid–compensated line has been successfully developed. The algorithm detects the fault–induced decaying DC or subsynchronous transient component and uses the result to adaptively select the appropriate relay settings.

Several conclusions can also be drawn from the results of this study:

1) The problems of using an impedance relay to protect a series compensated line is dependant upon many factors, such as the capacitor location, relay PT location, compensation degree, and operation of the capacitor protection circuits. Generally, a mid–compensated line with a large compensation degree ($> 50\%$) and versatile operating conditions cause more problems for an impedance relay than does an end–compensated line.

2) The fast relaying problems in protecting an end–compensated line can be solved effectively by placing the relay PT on the line side and adding a directional unit to the relay.

3) The fast relaying problems in protecting a mid–compensated line can be solved by applying the adaptive impedance relay algorithm developed in this study.

4) It is also feasible to implement the algorithm on the APT relay platform after some changes being made in the APT relay software structure.

5) Utilizing Electromagnetic Transient simulation software is an efficient way in developing new relay algorithms.

The fast relaying of series compensated line has become a more and more important issue today because of the increasing number of installed series capacitors. The adaptive impedance relay algorithm developed in this study is very promising. However, due to the complexity of the problem and the limited time, it has not been implemented on the APT relay platform and tested. The author would like to suggest following two areas for further development of this adaptive impedance relay:

1) Implementation of the adaptive impedance relay algorithm on the modified APT relay platform. This would be a direct continuation of this study. After the software structure of the current APT relay platform is modified, the algorithm should be implemented on it for further testing of the algorithm.

2) The implemented adaptive impedance relay should be tested on either a Real–Time Digital Simulator (RTDS) or a Transient Network Analyzer (TNA) to confirm its feasibilities. The test results should be compared with the results obtained using PSCAD/EMTDC to see if there are any discrepancies. Such a comparison will be useful for future relay algorithm development using PSCAD/EMTDC.

REFERENCES

[1] H. M. Yang, "Relay performance on the 500kV series compensated Dorsey–Forbes–Chisago transmission line", M.Sc. Thesis, University of Manitoba, Oct. 1991

[2] "IEEE power systems relaying committee working group report on EHV protection problems", IEEE Trans. PAS–100, No. 5, Sept./Oct. 1981, pp. 2399 – 2415

[3] G. Jancke, N. Fahlen and O. Nerf, "Series capacitors in power systems", IEEE Trans. PAS–94, No. 3, May/June 1975, pp. 915 – 925

[4] J. R. Hamann, S. A. Miske, I. B. Johnson and A. L. Courts, "A Zinc oxide varistor protective system for series capacitors", IEEE Trans. PAS–100, No. 3, Mar. 1981, pp. 929 – 937

[5] R. K. Aggarwal, A. T. Johns and A. Kalam, "Computer modelling of series compensated EHV transmission systems", Proc. IEE, Vol. 131, Part C, No. 5, Sept. 1984, pp. 188 – 196

[6] D. L. Goldsworthy, "A linearized model for MOV–protected series capacitors", IEEE Trans. PWRS–2, No. 4, Nov. 1987, pp. 953 – 957

[7] C. V. Narayan, "Distance protection of high–voltage lines containing series capacitors", Brown Boveri Review, Vol. 55, No. 7, 1968, pp. 372 – 382

[8] M. S. Sachdev and L. R. Tumma, "Protection of series compensated transmission lines – modelling and appraising", CEA publications, Paper No. 92–SP–183, 1992

[9] P. Muller, "Progress in the protection of series–compensated lines and in the determination of very high earth–fault resistances", Brown Boveri Review, Vol. 71, No. 2, 1981, pp. 102 – 103

[10] P. G. McLaren, R. Kuffel, A. Castro, D. Fedirchuk, K. Mustaphi and K. Sletten, "On site relay transient testing for a series compensation upgrade", IEEE Trans. PWRD–, No. , 199 , pp.

[11] B. S. A. Kumar, K. Parthasarathy, F. S. Prabhakara and H. P. Khincha, "Effectiveness of series capacitor in long distance transmission lines", IEEE Trans. PAS–89, No. 5/6, May/June 1970, pp. 941 – 951

[12] R. J. Marttila, "Performance of distance relay MHO elements on MOV–protected series–compensated transmission lines", IEEE Trans. PWRD–7, No. 3, July 1992, pp. 1167 – 1177

[13] M. M. Elkateb and W. J. Cheetham, "Problems in the protection of series compensated lines", IEE Conference publication on power system protection, No. 185, 1980, pp. 215 – 220

[14] S. E. M. de Oliveira, I. Gardos and E. P. Fonseca, "Representation of series capacitors in electric power system stability studies", IEEE Trans. PWRS–6, No. 3, Aug. 1991, pp. 1119 – 1125

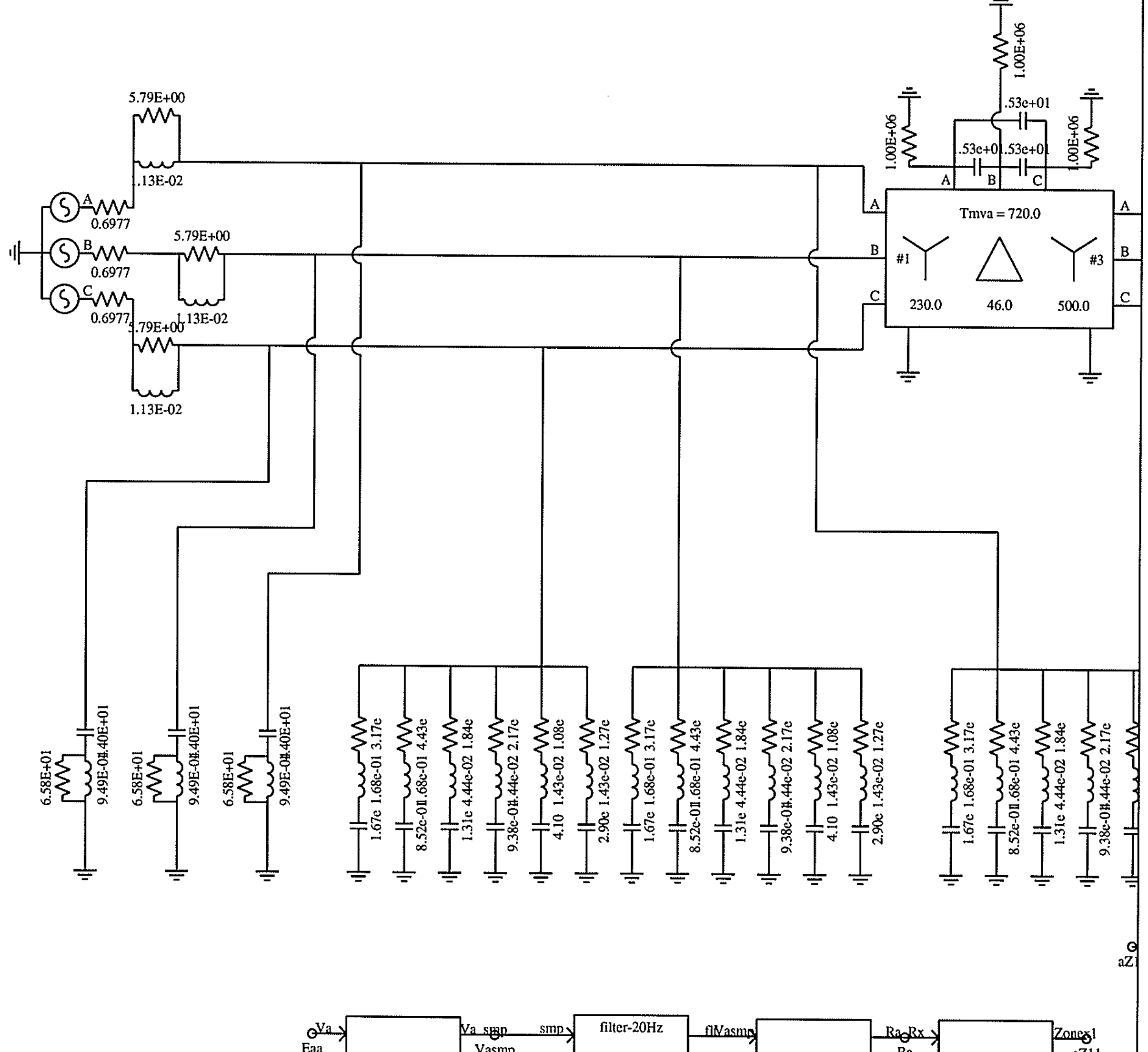
[15] MANITOBA HVDC RESERCH CENTRE " EMTDC User's Manual", 1988.

Appendix A

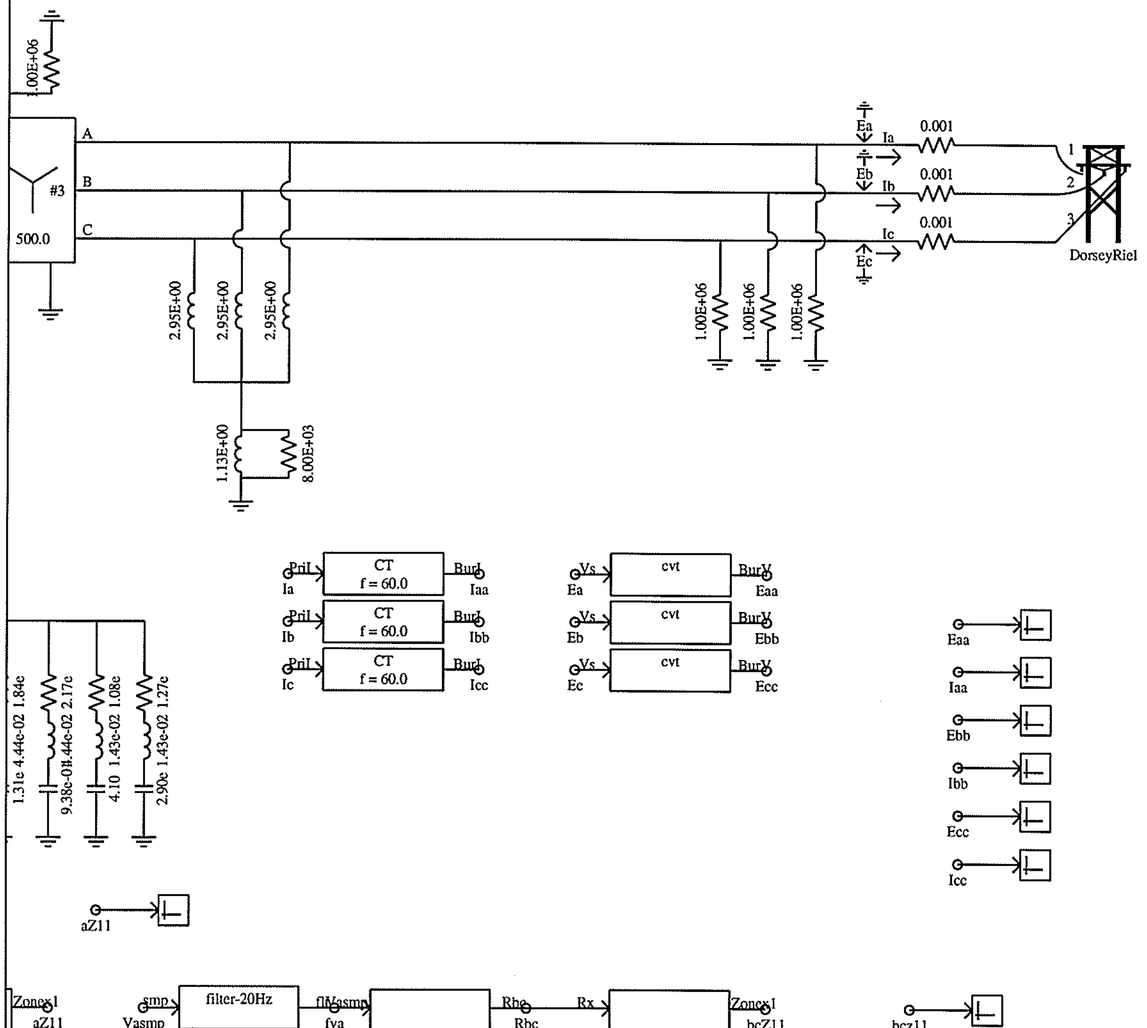
DORSEY-FORBES-CHISAGO SYSTEM & ADAPTIVE IMPEDANCE RELAY SCHEMATIC DRAFT DIAGRAM ON PSCAD/EMTDC

DORSEY-FORBES-CHISAGO SYSTEM & ADAPTIVE IMPEDANCE RELAY SCHEMATIC DRAFT DIAGRAM ON PSCAD/EMTDC

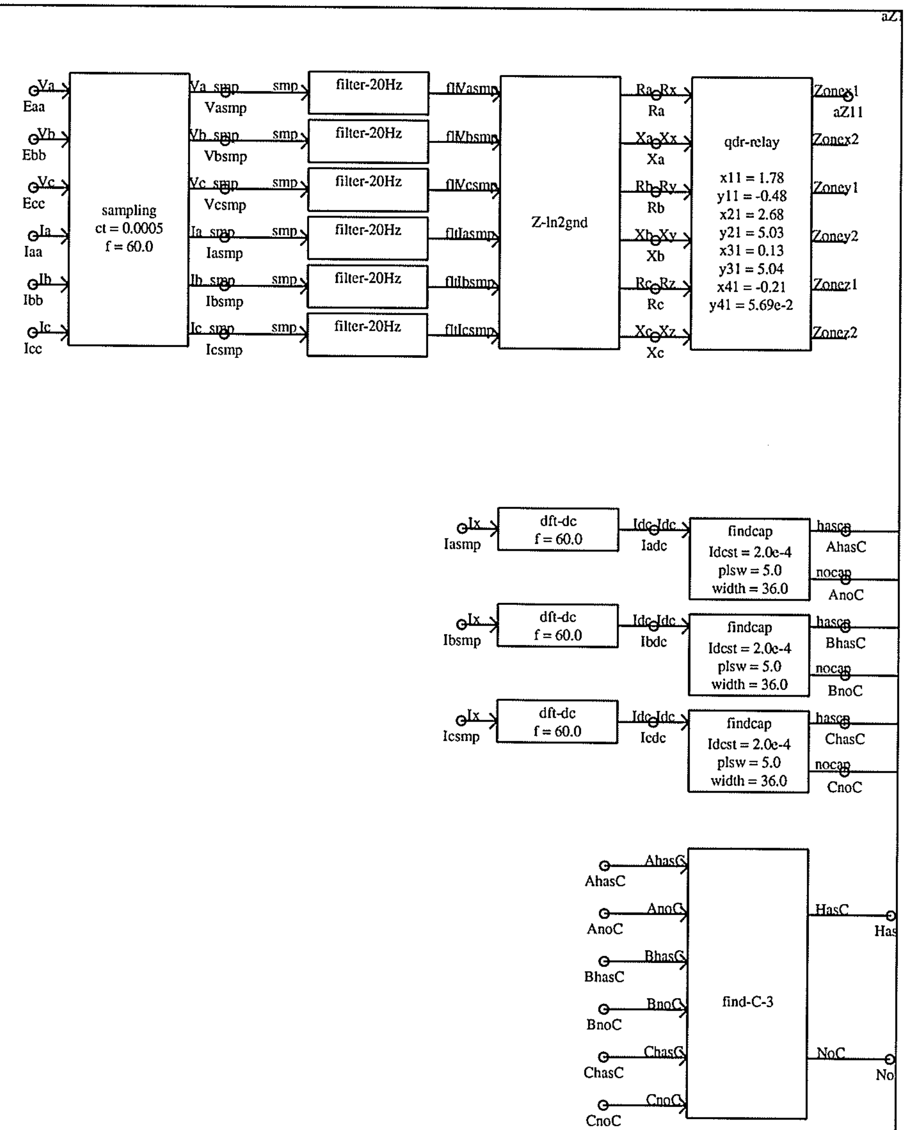
This appendix includes all draft diagrams for Dorsey–Forbes–Chisago system along with the adaptive impedance relay modelled on PSCAD/EMTDC. The first subsystem diagram (Dorsey substation with the adaptive impedance relay) is also printed in 4 divided diagram for easy reading. These 4 divided diagrams of the first subsystem are included at the end of this Appendix.



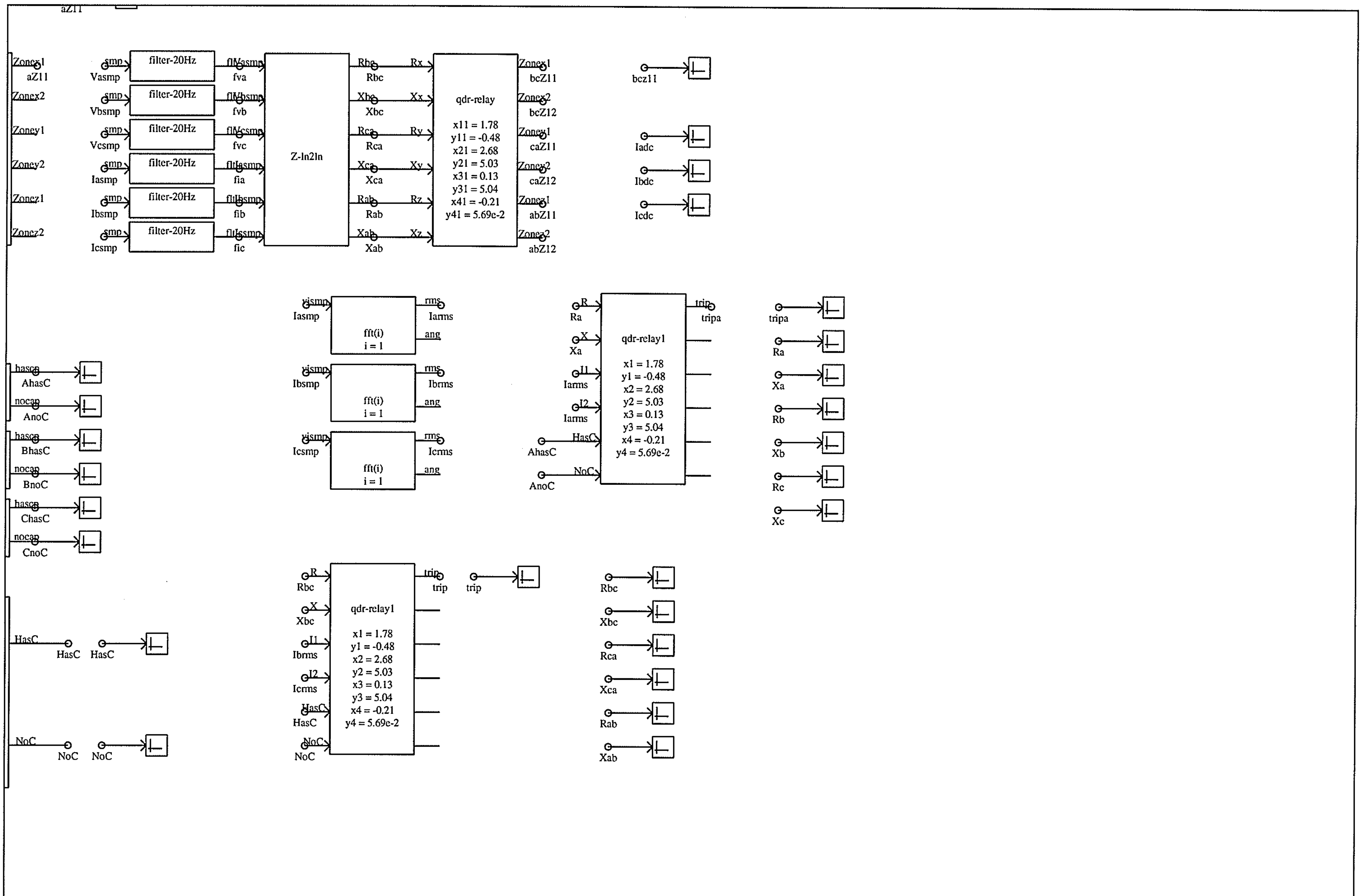
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*submin* Subsystem #1 of 15 Page 1 of 4



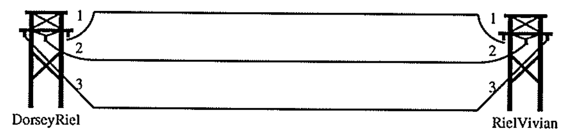
University of Manitoba, EE Dept.	Created:	April 29, 1993 (lxwu)	*submin*
DosFoChi	Last Modified:	February 02, 1994 (lxwu)	
	Printed On:	August 03, 1995 (lxwu)	Subsystem #1 of 15



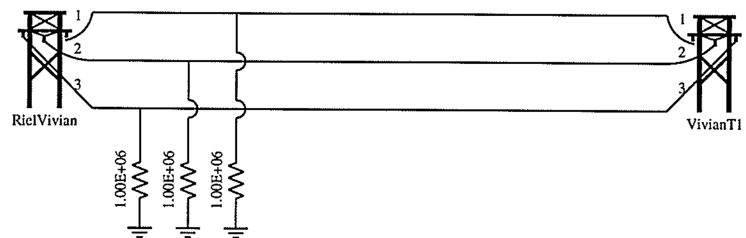
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*submin* Subsystem #1 of 15 — Page 3 of 4



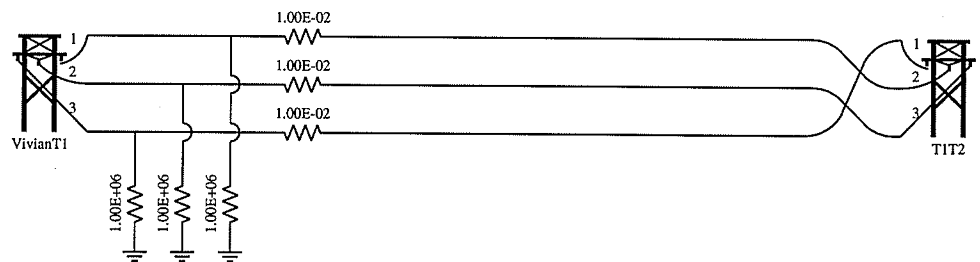
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*submin* Subsystem #1 of 15



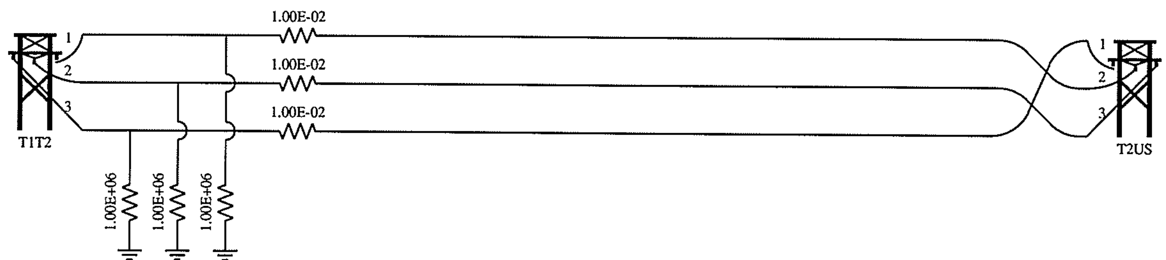
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub1* Subsystem #2 of 15



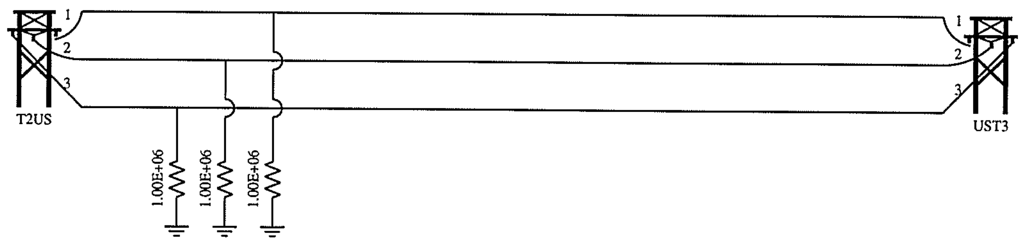
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub2* Subsystem #3 of 15



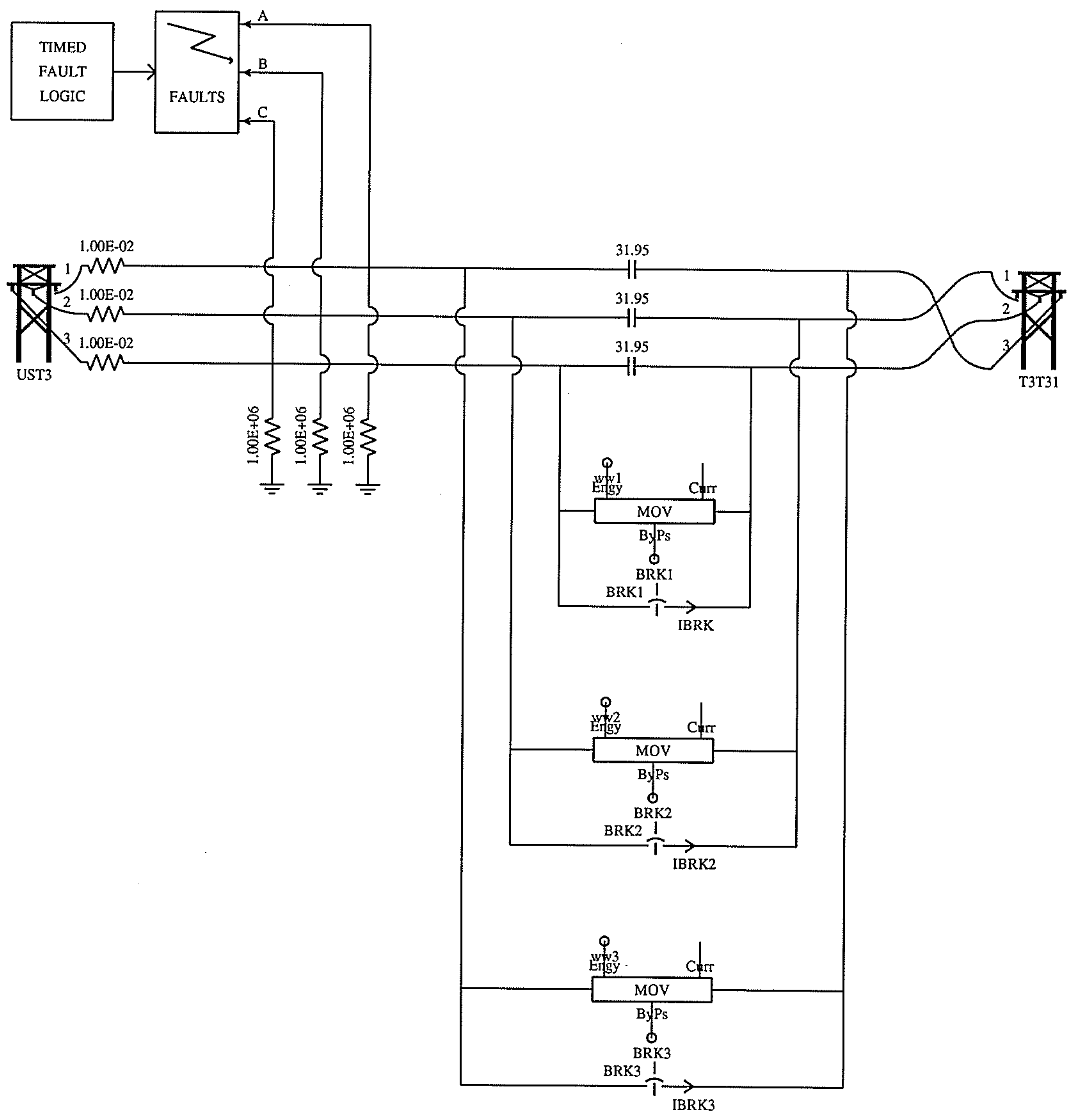
University of Manitoba, EE Dept.	Created:	April 29, 1993 (lxwu)	*sub3*
DosFoChi	Last Modified:	February 02, 1994 (lxwu)	
	Printed On:	August 03, 1995 (lxwu)	Subsystem #4 of 15



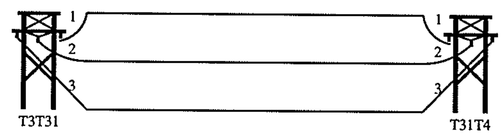
University of Manitoba, EE Dept.	Created: April 29, 1993 (lxwu)	*sub4*
DosFoChi	Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	Subsystem #5 of 15



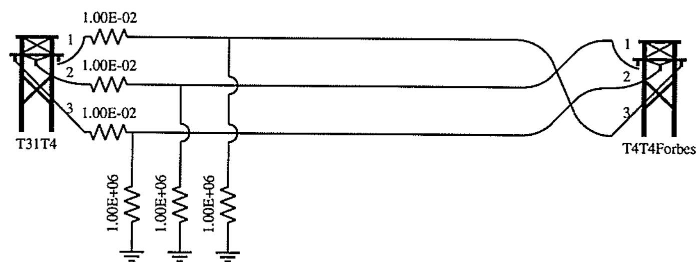
University of Manitoba, EE Dept. *DosFoChi*	Created: Last Modified: Printed On:	April 29, 1993 (lxwu) February 02, 1994 (lxwu) August 03, 1995 (lxwu)	*sub5* Subsystem #6 of 15



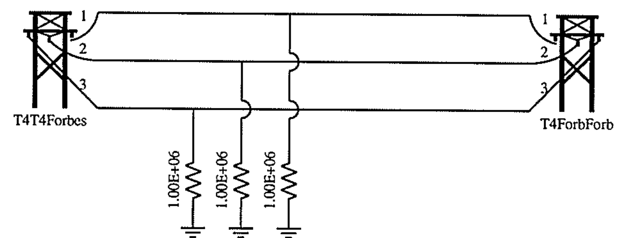
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub55* Subsystem #7 of 15



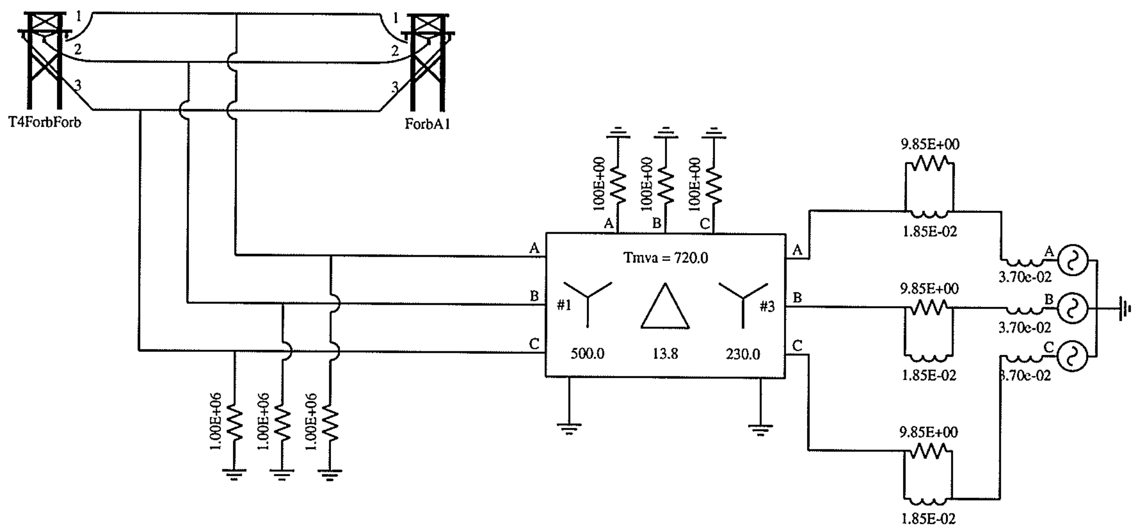
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub66* Subsystem #8 of 15



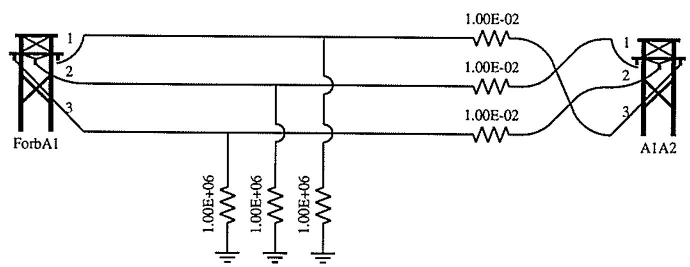
University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub6* Subsystem #9 of 15



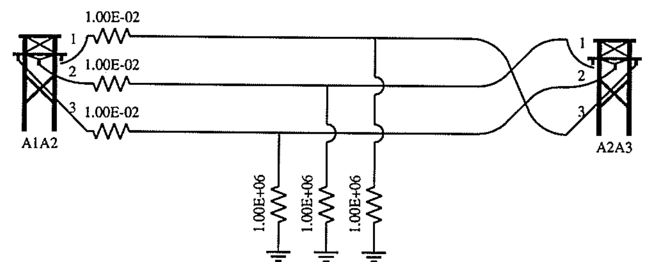
University of Manitoba, EE Dept. *DosFoChi*	Created: Last Modified: Printed On:	April 29, 1993 (lxwu) February 02, 1994 (lxwu) August 03, 1995 (lxwu)	*sub7* Subsystem #10 of 15



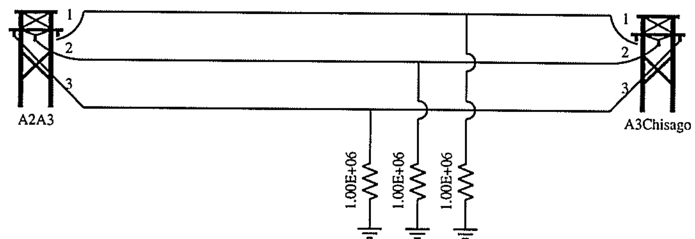
University of Manitoba, EE Dept. *DosFoChi*	Created: Last Modified: Printed On:	April 29, 1993 (lxwu) February 02, 1994 (lxwu) August 03, 1995 (lxwu)	*sub8* Subsystem #11 of 15



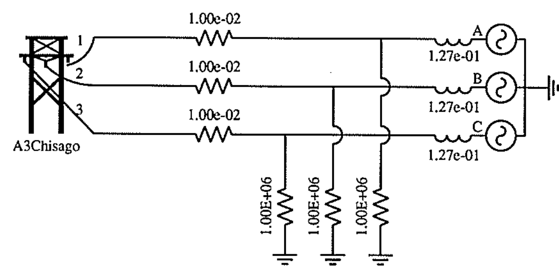
University of Manitoba, EE Dept. *DosFoChi*	Created: Last Modified: Printed On:	April 29, 1993 (lxwu) February 02, 1994 (lxwu) August 03, 1995 (lxwu)	*sub9* Subsystem #12 of 15



University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub10* Subsystem #13 of 15



University of Manitoba, EE Dept. *DosFoChi*	Created: Last Modified: Printed On:	April 29, 1993 (lxwu) February 02, 1994 (lxwu) August 03, 1995 (lxwu)	*sub11* Subsystem #14 of 15



University of Manitoba, EE Dept. *DosFoChi*	Created: April 29, 1993 (lxwu) Last Modified: February 02, 1994 (lxwu) Printed On: August 03, 1995 (lxwu)	*sub12* Subsystem #15 of 15