STATIC AND DYNAMIC IMPACTS OF SIX-PHASE POWER TRANSMISSION SYSTEM

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To my beloved wife, Noor Azlina binti Othman
for her support and confidence in me.

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ABSTRACT

Electricity is considered as the driving force for a country, which is undergoing rapid industrialization. Constraints on the availability of land and planning permission for overhead transmission lines have renewed interest in techniques to increase the power carrying capacity of existing Right-Of-Ways (ROW). Six-phase (6-Φ) transmission appears to be the most promising solution to the need to increase the capability of existing transmission lines and at the same time, respond to the concerns related to electromagnetic fields. One of the main advantages of 6-Φ transmission is that a 6-Φ line can carry up to 73% more electric power than a three-phase (3-Φ) double-circuit line on the same transmission ROW. However, this conversion will have impacts on the power system operations. This thesis presents the static and dynamic impacts of 6-Φ transmission system. The study initially involved the development of 6-Φ transmission system model from the 3-Φ transmission line. The models were developed using the *Power System Computer Aided Design/Electromagnetic Transient and Direct Current* (PSCAD/EMTDC). In this research, the load flow studies, fault analysis and transient stability were conducted on the IEEE Test Systems and 19-Bus TNB South Kelantan Equivalent System. These studies were performed in sufficient detail to determine how the 6-Φ conversion will affect steady state operation, fault current duties, and system stability. A laboratory prototype of Kuala Krai to Gua Musang, Kelantan TNB Thevenin equivalent systems was developed to validate the simulation results. From the simulation results, it has been shown that the IEEE Test Systems and 19-Bus TNB South Kelantan Equivalent System with 6-Φ single-circuit transmission has better stability limits compared to the 3-Φ double-circuit transmission. It is shown that the voltage level at all buses remains within acceptable limit. It is also discovered that the fault current magnitude of the 6-Φ single-circuit transmission is less as compared to the 3-Φ double-circuit transmission.

ABSTRAK

Tenaga elektrik merupakan pemacu kepada kepesatan sektor perindustrian negara. Kesukaran mendapatkan kebenaran dan tanah untuk membina talian penghantaran atas yang baru telah menarik minat terhadap teknik meningkatkan keupayaan pemindahan kuasa menggunakan talian sedia ada. Sistem penghantaran kuasa enam-fasa (6-Φ) muncul sebagai satu penyelesaian bagi meningkatkan keupayaan talian sedia ada dan pada masa yang sama, ianya mengambilkira kesan medan elektromagnet. Kebaikan utama sistem penghantaran 6-Φ ialah dapat membawa 73% lebih kuasa berbanding sistem penghantaran talian-berkembar tiga-fasa (3-Φ) dengan menggunakan ruang talian atas yang sama. Walaubagaimanapun, penukaran ini mempunyai kesan terhadap pengoperasian sistem kuasa. Tesis ini mempersembahkan kesan statik dan dinamik sistem penghantaran 6-Φ. Kajian dimulakan dengan menghasilkan model sistem penghantaran 6-Φ daripada talian penghantaran 3-Φ. Model tersebut dibina menggunakan program PSCAD/EMTDC. Penyelidikan ini mengkaji aliran beban, arus kerosakan, dan kestabilan fana bagi beberapa sistem ujian IEEE dan juga Sistem Setara TNB Selatan Kelantan 19-Bas. Kajian ini dilakukan dengan teliti untuk menentukan kesan penukaran kepada sistem 6-Φ mempengaruhi operasi keadaan mantap, sambutan arus kerosakan, dan kestabilan sistem. Untuk menentusahkan keputusan simulasi, satu prototaip makmal bagi litar setara Thevenin Sistem TNB, Kuala Krai ke Gua Musang, Kelantan telah dibina. Hasil simulasi menunjukkan bahawa Sistem Ujian IEEE dan Sistem Setara TNB Selatan Kelantan 19-Bas dengan talian penghantaran 6-Φ mempunyai had kestabilan yang lebih baik berbanding dengan sistem penghantaran talian-berkembar 3-Φ. Ia juga menunjukkan paras voltan pada semua bas tetap berada dalam had yang dibenarkan. Selain itu, magnitud arus kerosakan didapati lebih rendah apabila penghantaran talian-tunggal 6-Φ digunakan berbanding talian-berkembar 3-Φ.

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LIST OF ABBREVIATIONS

AC	-	Asynchronous current
APS	-	Allegheny Power Services Corporation
DC	-	Direct current
DOE	-	Department of Energy
EHV	-	Extra-high voltage
EPRI	-	Electric Power Research Institute
ESEERCO	-	Empire State Electric Energy Research Corporation
GSU	-	Generator step-up
HPO	-	High phase order
HVDC	-	High-voltage DC
MATLAB	-	Matrix laboratory software
MATPOWER	-	A MATLAB™ Power System Simulation Package
NYSEG	-	New York State Electric and Gas Corporation
NYSERDA	-	New York State Energy Research and Development Authority
PSCAD/ EMTDC	-	Power System Computer Aided Design/ Electromagnetic Transient for Direct Current
PTI	-	Power Technologies Incorporated
SIL	-	Surge Impedance Loading
TNB	-	Tenaga National Berhad
UHV	-	Ultra-high voltages

LIST OF SYMBOLS

a	-	Transformer turn ratio or $1\angle 120°$ in polar number
C	-	Capacitance, μf
E	-	Excitation voltage
f	-	Frequency, Hz
G	-	Machine rating in, MVA
H	-	Inertia constant or Height, m
I	-	Current, A
L	-	Inductance, mH
M	-	Angular momentum, joule-sec/radian
N	-	Number (of phases/phase conductors, turns, etc.) or Neutral
n	-	Speed
P	-	Real power
P_a	-	Accelerating power
P_e	-	Electrical output of machine
P_m	-	Mechanical power input of machine
S_{KVA}	-	Three-phase apparent power, kVA
T_a	-	Torque, Nm
V	-	Voltage
V_P	-	Phase-to-neutral voltage
V_L	-	Phase-to-phase voltage

V_{LP}	-	Phase-to-phase voltage at primary side
V_{LS}	-	Phase-to-phase voltage at secondary side
V_{PP}	-	Phase-to-neutral voltage at primary side
V_{PS}	-	Phase-to-neutral voltage at secondary side
W	-	Width, m
x	-	Positive-sequence impedance, Ω
x_e	-	System reactance, Ω
x_s	-	Generator synchronous reactance, Ω
X_L	-	Leakage Reactance as seen from winding 1, Ω
y	-	Admittance, mho
z	-	Impedance, Ω
Z_c	-	Positive-sequence surge impedance of the line, Ω
Y-Y	-	Wye-Wye connection of the transformer winding
Y-Δ	-	Wye-Delta connection of the transformer winding
Δ-Y	-	Delta-Wye connection of the transformer winding
Δ-Δ	-	Delta-Delta connection of the transformer winding
α	-	Angular acceleration, radians/second^2
δ	-	Angle difference between the voltages, degree
θ	-	Angular displacement, radians
π	-	3.1416 radians or 180°
ω	-	Angular velocity, radians/second
3PDC	-	Three-phase double-circuit
6PSC	-	Six-phase single-circuit
3-Φ	-	Three-phase
6-Φ	-	Six-phase

3-Φ-to-6-Φ	-	Three-phase-to-six-phase
6-Φ-to-3-Φ	-	Six-phase-to-three-phase

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Electricity is considered as the driving force for a country, which is undergoing rapid industrialization. Traditionally, the need for increasing power transmission capability and more efficient use of ROW space has been accomplished by the use of successively higher system voltages. Constraints on the availability of land and planning permission for overhead transmission lines have renewed interest in techniques to increase the power carrying capacity of existing ROWs. High phase order (HPO) transmission is the use of more phases than the conventional 3-Φ transmission system. The increased interest in HPO electric power transmission over past thirty years can be traced on a CIGRE paper published by L. D. Barthold and H. C. Barnes [1]. Since then, the concept of HPO transmission has been described in the literature in several papers and reports.

Among the HPO techniques, 6-Φ transmission appears to be the most promising solution to the need of increasing the capability of existing transmission lines and, at the same time respond to the concerns related to electromagnetic fields. One of the main advantages of 6-Φ transmission is that a 6-Φ line can carry up to 73% more electric power than a 3-Φ double-circuit line on the same transmission ROW [2]. For this reason, the current research has been carried out to have a better picture and clearer understanding of the 6-Φ power transmission system. This research studies the static and dynamic impacts during normal and abnormal operating conditions for electric power system considering 3-Φ-to-6-Φ conversions of selected transmission lines in an electric energy system.

The load flow analysis, fault analysis, and transient stability analysis were performed on various test systems including IEEE Test Systems and 19-Bus TNB System in sufficient detail using the graphical electromagnetic transient simulation program, PSCAD/EMTDC in time domain basis to determine how 6-Φ conversion will affect steady state operation, fault current duties, and system stability. The study has been implemented in 5 cases namely Test System I to Test System IV and also 19-Bus TNB System.

The conversion model from 3-Φ double-circuit lines to 6-Φ have been developed for all the test systems. The simulation model consists of a static AC equivalent circuit, generators, exciters, hydro governors, converter transformer, transmission lines and loads. The parameters of equivalent AC networks, generators, exciters, and etc. are modelled through the PSCAD/EMTDC program.

1.2 Literature Reviews

Electric power transmission was originally developed in the direct current (DC) mode. In 1878, Thomas A. Edison began a work on the electric light and formulated the concept of centrally located power station with distributed lighting serving the surround area. He perfected his light by October 1879, and the opening of his historic Pearl Street Station in New York City on September 4, 1882 has marked the beginning of the electric utility industry. At Pearl Street, DC generators, then called the dynamos, were driven by steam engines to supply an initial load of 30kW for 110V incandescent lighting to 59 customers in a one-square-mile area. From this moment; in 1882 through 1972, the electric utility industry grew at a remarkable pace. A growth based on continuous reductions in the price of electricity was primarily to technological accomplishment and creative engineering. The introduction of the practical DC motor by Sprague Electric, as well as the growth of incandescent lighting, promoted the expansion of Edison's DC system. The development of three-wire 220 V DC systems allowed load to increase somewhat, but as transmission distances and loads continued increase, voltage problems were encountered. These limitations of maximum distance and load were overcome in 1885 by William Stanley's development of a commercial practical transformer [3]. With the presence of transformer, the ability to transmit power at high voltage with corresponding lower current and lower line-voltage drops have made AC more attractive than DC.

The first 1-Φ AC line in the United States operated in 1889 in Oregon, between Oregon City and Portland (21km at 4kV). The growth of AC systems was further encouraged in 1888 when Nikola Tesla presented a paper at a meeting of America Institute of Electrical Engineers, describing 2-Φ induction and synchronous motors, which has made it as an evident to promote the advantages of polyphase versus 1-Φ system. The first 3-Φ line in Germany became operational in 1891, transmitting power 179km at 12kV. The first 3-Φ line in the United States was in California which became operational in 1893, transmitting power over 12km distance at 2.3kV. The 3-Φ induction motor conceived by Tesla went on to become the workhorse of the industry. There has been consequent increment in 3-Φ transmission voltages in USA during that era. From Edison's 220V three-wire DC grids to 4kV 1-Φ and 2.3kV 3-Φ transmission systems, AC transmission voltages in United States have risen progressively to 150, 230, 345, 500, and now 765kV. An ultra-high voltages (UHV) above 1000kV are now being studied. The incentives for increasing transmission voltages have been:

a) increment in transmission distance and transmission capacity
b) smaller line-voltage drops
c) reduction in line losses
d) reduction in ROW requirements per MW transfer
e) lower capital and operating costs of transmission.

For the purpose of transmitting power over very long distances; it may be economical to convert the EHV AC to EHV DC, transmit the power over two lines, and invert it back to AC at the other end. This is based on the fact that, the EHV DC has lower losses in transmission line and also has no skin effect [3]. In 1954, the first modern High-Voltage DC (HVDC) transmission line was put into operation in Sweden between Vastervik and the island of Gotland in the Baltic Sea [3]. It was operated at 100kV for a distance of 100km. The first HVDC line in the United States was the ±400kV, 1360km Pacific Intertie line installed between Oregon and California in 1970. As of 2000, four other HVDC lines up to 400kV and five back-to-back AC-DC links had been installed in the United States, and a total of 30 HVDC lines up to 533kV had been installed worldwide. For an HVDC line embedded in an AC system, solid-state converters at both ends of the DC line operate as rectifiers and inverters. Since the cost of an HVDC transmission line is less than that of an AC line with the same capacity, the additional cost of converters for DC transmission is offset when the line is long enough. Studies show that it is advantageous to consider overhead HVDC transmission lines when the transmission distance is longer than 600km [3]. HVDC lines have no reactance and are capable of transferring more power for the same conductor size than AC lines. DC transmission is especially advantageous when two remotely located large systems are to be connected. The DC transmission tie line acts as an asynchronous link between the two rigid systems eliminating the instability problem inherent in the AC links. The main disadvantage of the DC is the production of harmonics which requires filtering, and a large amount of reactive power compensation required at both ends of the line [3].

The HPO electric power transmission introduced in [1] sparked the industry curiosity by suggesting that with a concern over the aesthetic impact of transmission lines, it seem timely to review some fundamental principals of overhead transmission and examine the space efficiency of overhead conductors. One variable which relates to that efficiency is the number of phases. The work had focused the industry on the practical aspect of concepts that were first explained by Fostesque [4] in 1918 and E. Clark [5] in 1943. Since this corner stone work, much has been added to the available knowledge base on HPO transmission primarily in the areas of feasibility considerations, analysis of system characteristics and system protection. In the late 1970s, W. C. Guyker *et al*. [6] extended the transmission concept by describing fault analysis methodologies and symmetrical component theory. They also assessed the feasibility of upgrading an existing 138kV line to 6-Φ [7] to increase the power transmission capability by 73% while reducing conductor field gradients and improving system stability which potentially could obtain public acceptance since the nominal voltage of the line would remain unchanged. These authors also lain ground work for EPRI Research in 1984 on fault protection for HPO transmission line [8].

Allegheny Power Services Corporation (APS) in cooperation with West Virginia University began seriously investigating the details of an HPO designed in 1976. Their studies, funded partly by the National Science Foundation, showed that the HPO transmission should be considered as a viable alternative to the conventional 3-Φ transmission system. They completed detailed analysis of HPO designs and protection philosophies, but stopped short of actually demonstrating the technologies on an operating line. Load projections for their service territory were reduced, thus eliminating the incentive to pursue increased power transfer capabilities. The project was abandoned; however, through their initiative, APS paved the way for future research [9].

A feasibility analysis of HPO transmission was conducted by J. Steward and D. Wilson for the U.S. Department of Energy 1976/1977. This initial study addressed the definition of system voltage, developed fundamental frequency system parameters (symmetrical components, transmission line impedances and unbalanced operation), considered transient over voltage performance (switching surges, rate-of-rise of recovery voltage on circuit breakers and lightning), evaluated electrical environmental parameters (electric fields, radio and audio noise) and gave initial consideration to hardware and equipment, mechanical considerations and economics. The results of this feasibility analysis were sufficient favourable that the U.S. Department of Energy (DOE) and New York State Energy Research and Development Authority (NYSERDA) sponsored construction of 6-Φ and 12-Φ test line at Malta, New York. Contracts were issued to Power Technologies Incorporated (PTI) to develop design calculations for corona effects and electric field effects of the first 6-Φ transmission test line. The line was build at NYSERDA's Malta, New York testing facility. A final report issued in 1978 [10] concluded that 6-Φ transmission “can provide the same power transfer capacity as 3-Φ with significantly less ROW for the same electric field and audible noise criteria, smaller transmission structures, and reduced overall cost”. Based upon these results, it was recommended that the research to be continued into 12-Φ designs [10-11].

In 1985, PTI was awarded to study 12-Φ transmission and to construct a 12-Φ line. The project was cofunded by DOE, NYSERDA and Empire State Electric Energy Research Corporation (ESEERCO). It was through this project that NYSEG (New York State Electric and Gas Corporation) became more involved. The final report for this project [9] was released and showed that 12-Φ also appears to offer significant benefits over 3-Φ options depending upon power transfer capacities required and given the fact that the 12-Φ line can be designed for optimum 12-Φ operation. In any event, the PTI project has confirmed the technology in a test situation and all that remained was to implement high-phase transmission into an existing transmission network. NYSEG expressed an interest to become involved in this project demonstration. Because of this reason, the demonstration project was developed.

For a demonstration project, a 6-Φ system was selected since it presents an optimum value between the proportional increased in loading and the proportional increased in surge impedance obtained by increasing the number of phases with the increase in power transfer capability. The project which was conceived in 1988 had as its primary objective, to demonstrate the commercial feasibility of HPO transmission by electrically reconfiguring the existing 115kV owned and operated by NYSEG into a 6-Φ single-circuit line operated at 93kV. The needs for this demonstration project stems from the industry’s need for high reliability demanded by the public coupled with a conservative approach to new technology. To fill the void, the ESEERCO has undertaken the HPO project, and in a collaboration with NYSEG have selected the Goudey-Oakdale line as the most likely candidate for the demonstration project after an exhaustive search of all 3-Φ double-circuit lines within New York State with due consideration given to length of line, outage potential, extent of modifications required and accessibility to conduct tests [12].

Reference [13] presents the feasibility of 6-Φ transmission system in terms of insulation performance, corona and field effects, and load flow and system stability. Based on the detailed insulation coordination analysis, the study has shown that Goudey-Oakdale line capable of operation at 97.6 kV 6-Φ and existing clearances are adequate for power frequency and switching surge considerations. This paper also concluded that lightning performance is essentially unchanged, radio and audible noise are within acceptable limits and steady state and contingency cases will not adversely affect or degrade the NYSEG system by the conversion of Goudey-Oakdale line.

Referring to reference [14], the potential advantages of NYSEG HPO as a means of field mitigation are discussed. It is concluded that, it is possible to develop HPO alternative to 3-Φ lines with comparable power handling capacity, significantly smaller size and at the same or reduced ground level fields. The performances of the protection system that was used for the Goudey-Oakdale test line are discussed in reference [15]. The protection system for the first commercially Goudey-Oakdale operated 6-Φ transmission line consist of state of the art microprocessor based relays designed for protection of conventional 3-Φ systems. The study done from reference [15] shown that, the 6-Φ protection is capable to operate according to the trip and reclosure requirements for any fault combination. Furthermore, this reference also reviewed the comparison between the calculated and measured fault currents at both ends of the 6-Φ line. It is also proven that an HPO transmission line can be modelled accurately for any type of faults in a conventional short circuit program.

Reference [16] gives the experimental results of the NYSEG demonstration project in term of corona and field effects on an operating 6-Φ transmission line. This study has given verification to available methods for the calculation of electric and magnetic fields, radio noise and audio noise from the 6-Φ overhead lines. From references [13-16], it has been shown that the 6-Φ transmission system can provide the same power transfer capability with lower ROW or can transfer 73% more power for the same ROW as compared to the 3-Φ double-circuit system. Some of the advantages of using the 6-Φ transmission system are increased transmission capability, increased utilization of ROW, lower corona effects, lower insulation requirement and better voltage regulation. These benefits are among the reasons why power system engineers are enticed to consistently pursue knowledge on the power system.

In 1998, Landers *et al.* [17] had done some research works on the comparison of installation costs for constructing a standard 115kV 3-Φ double-circuit transmission line to build 66kV 6-Φ transmission line which also indicated that the use of 6-Φ transmission can be a cost effective solution. It was found that, the cost penalty for constructing a new 6-Φ line versus a 3-Φ line of the same voltage level is not excessive, particularly if physical constraints exist. Therefore they concluded that 6-Φ should be considered when developing the optimum line that will meet the physical, environmental and regulatory constraints of a specific project. After 1998 till recently, several researches on 6-Φ fault analysis and reliability studies have been published since 1998 as reported in [18-44].

Reference [44] demonstrates various experiences with the use of the PSCAD/EMTDC software. This work describes the development of suites of simulation examples or "laboratory experiments" for the use in undergraduate and graduate power engineering courses. The examples used in three separate courses are presented: Power Electronics, HVDC Transmission and Power System Relaying. In addition, the use of PSCAD/EMTDC in various projects is also presented. Experiences with the use of the PSCAD/EMTDC software have been positive and have enhanced the quality of research and teaching. Besides, the simulation based approaches proved to be very effective.

1.3 Objectives and Scope

The major objective of this research is to analyse the static and dynamic impacts of power system with a 6-Φ converted transmission lines. The analyses include load flow analysis, fault analysis and transient stability analysis. Its measurable objectives are as below:

a) To conduct a load flow analysis of test systems and 19-Bus TNB System considering conversion of its existing 3-Φ double-circuit lines into 6-Φ single-circuit line.

b) To carry out a fault analysis of the same systems as in (a). This will determine the adequacy of existing switchgear's short circuit capacity for permitting 3-Φ-to-6-Φ conversions.

c) To make a transient stability analysis of the same systems as in (a). This will determine the impacts of conversion on the security of the system following outage of a converted line.

d) To verify the computer simulation results (a to c) by developing a laboratory prototype of the Kuala Krai to Gua Musang, Kelantan TNB Thevenin equivalent system and then conducting tests on that prototype.

The scope of this study can be summarized as follows:

a) Development of 3-Φ double-circuit transmission and 6-Φ single-circuit transmission models by using PSCAD/EMTDC program.

b) Simulations of the developed models were consequently implemented using PSCAD/EMTDC.

c) Implementation of comparative studies for 3-Φ double-circuit and 6-Φ single-circuit transmission.

d) Development of a laboratory prototype for the Kuala Krai to Gua Musang, Kelantan TNB Thevenin equivalent considering conversion of its existing 3-Φ double-circuit lines into 6-Φ single-circuit ones.

e) Validation of the developed prototype through the comparisons between the computer simulation and test results.

1.4 Contributions

The research work that constitutes this thesis is a unique and original contribution to electric power engineering and particularly to the field of power transmission systems. The numerous research findings have been documented as publications in peer reviewed national and international conference proceedings. References [41] to [43] represent the author's principal publications associated with this research.

The documentation of this thesis and the associated publications, and other references serve as a comprehensive collection of literature on 6-Φ transmission system. The precise contributions of this research can be summarized as follows:

a) Analysis of the static and dynamic impacts of electric systems with 3-Φ double-circuit transmission.

b) Analysis of the static and dynamic impacts of electric systems with 6-Φ single-circuit transmission.

c) Implementation on comprehensive comparisons between the results for both electric systems with 3-Φ double-circuit and 6-Φ single-circuit transmission.

d) Development of a prototype of the Kuala Krai to Gua Musang, Kelantan TNB Thevenin equivalent considering conversion of its existing 3-Φ double-circuit lines into 6-Φ single-circuit ones that can be used for the demonstration purposes.

e) Modeling of the real life 19-Bus TNB System into the PSCAD/EMTDC V4.1 simulation package is also a part of the research contribution.

1.5 Thesis Structure

This thesis is primarily concerned with the understanding, modeling, and analysing of static and dynamic impacts of 3-Φ-to-6-Φ conversion of selected transmission line in electric power systems. All the work done in this research is presented systematically in 7 chapters.

Chapter 2 and Chapter 3 provide the literature reviews of this research. Chapter 2 presents a thorough basic theory of 6-Φ power transmission system. The advantages of 6-Φ transmission system over 3-Φ transmission systems are also described in this chapter. Introduction to the static and dynamic impacts of power system with 6-Φ converted transmission line is covered in Chapter 3. The aims of this chapter are to provide the basic theory of load flow analysis, fault analysis, and transient stability analysis of power system considering conversion of 3-Φ double-circuit to 6-Φ single-circuit transmission.

Chapter 4 is devoted to the modelling of 6-Φ transmission systems using the PSCAD/EMTDC as derived in Chapter 2. System configuration, PSCAD components used and methodologies of analysis are also described in this chapter. Chapter 5 described about development of the laboratory prototype. All the analysis and simulation results along with the discussions are shown in the Chapter 6. In Chapter 7, the conclusions of the research and recommendations for the future work can be found. Finally, this thesis is ended by list of References and Appendix.