A SCALED-DOWN PROTOTYPE OF TRANSMISSION LINE FOR SIX- PHASE CONVERSION UNDER TRANSIENT OVERVOLTAGE

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ABSTRACT

Six-phase transmission line (SPTL) system can be an alternative method to increase the existing transmission line power transfer capability to meet the increasing electrical energy demand of the future. In Malaysia, understanding and the knowledge of high phase conversion can be considered very shallow to contribute toward the realization of the six-phase transmission line. Tests on actual line settings and configuration which are needed during a study are the main challenges to researchers who have limited access to the lines. This is due to the fact that any changes to the actual line settings and configurations while the systems is running normally will not be appreciated by the power utilities who are committed to minimizing any cause of interruption to their supply system. To overcome this problem, this research project came out with broadly two programs. The first part is to carried out simulation studies of the SPTL, and the second part of this project focuses on construction a scaled down model of SPTL. The strategy is to compare the result of the study from the experimental point of view with the results obtained from simulation. Thus, the research could come out with the full understanding of SPTL system in term of its steady state and switching transient phenomena. In order to realize the SPTL system, the simulation study uses the ATP/EMTP incorporates two sets of three-phase transformer with other apparatus of the high voltage transmission system to come out with SPTL system model. In the experimental setup, the Tenaga Nasional Berhad (TNB) 132kV transmission line running from Kuala Krai to Gua Musang was used as the basis for the development of the scaled down power transmission line model (SDPTLM) of the SPTL system. From the research studies, it was found that the magnitude of phase-to-ground and phase-to-phase switching surges of the converted system is much higher compared to the allowable crest voltage value of parent system. It was approximately 2.02 – 8.20 pu for both switching energization and switching de-energization. The percentage difference between the experimental and simulation was in the range 1.42 to 2.22. The switching energization and de-energization as well as steady state studies carried out in this work can be used by utility companies such as TNB as feasibility studies when converting their existing three-phase transmission lines to SPTL in future.

ABSTRAK

Sistem Talian Penghantaran Enam Fasa (STPEF) boleh menjadi satu kaedah alternatif untuk meningkatkan keupayaan pemindahan kuasa talian penghantaran sediaada bagi memenuhi peningkatan permintaan tenaga pada masa hadapan. Di Malaysia, kefahaman ilmu masyarakat terhadap penukaran fasa tinggi amat rendah bagi menyumbang kepada kesadaran terhadap penggunaan STPEF. Ujian dan konfigurasi pada talian sebenar diperlukan ketika kajian dilakukan merupakan satu cabaran utama kepada penyelidik-penyelidik yang mempunyai pendedahan terbatas terhadap talian tersebut. Ini adalah kerana, sebarang perubahan terhadap konfigurasi dan pengesetan pada talian sebenar pada sistem yang sedang beroperasi secara baik tidak dibenarkan oleh pihak pembekal kuasa yang lebih mengutamakan pengurangan punca ganguan terhadap sistem kuasa mereka. Untuk mengatasi masalah ini, projek penyelidikan ini menekankan dua bahagian utama dalam kajiannya. Bahagian pertama adalah menjalankan kajian simulasi terhadap STPEF, dan pada bahagian kedua adalah menghasilkan model skala kecil STPEF. Strateginya adalah dengan membandingkan hasil keputusan dari kajian ujikaji makmal dengan keputusan dari ujian simulasi. Ini akan menghasilkan satu kepahaman penuh terhadap sistem STPEF dari sudut fenomena keadaan fana dan ubahtika pensuisan. Di dalam kajian simulasi, untuk memahami sistem STPEF, perisian ATP/EMTP digunakan bagi menggabungkan dua set alat ubah tiga fasa dengan sistem talian penghantaran voltan tinggi dengan menghasilkan model sistem STPEF. Manakala bagi persiapan ujikaji makmal, talian penghataran TNB bervoltan 132 kV yang beroperasi dari Kuala Krai ke Gua Musang telah digunakan sebagai panduan dan rujukan bagi pembinaan model STPEF berskala kecil. Daripada kajian yang dijalankan, adalah didapati bahwa magnitud pusuan pensuisan untuk fasa ke bumi dan fasa ke fasa bagi sistem STPEF adalah lebih tinggi berbanding dengan nilai voltan sistem yang dibenarkan pada sistem sediaada. Ianya adalah dianggarkan antara 2.02 pu – 8.20 pu untuk kedua-dua pensuisan pentenagaan dan pensuisan dinyah tenaga. Peratus perbezaan antara ujikaji makmal dan simulasi adalah dalam julat 1.42% to 2.22%. Hasil ujikaji pentenagaan dan nyah tenaga dan juga kajian keadaan mantap yang telah dijalankan di dalam kajian ini boleh digunakan oleh syarikat pembekal tenaga seperti TNB sebagai kajian kebolehlaksanaan apabila penukaran system talian penghantaran tiga fasa sedia ada kepada SPTPEF dilaksanakan dimasa hadapan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
ACSR	-	Aluminium Conductor Steel Reinforced
ANSI	-	American National Standards Association
BIL	-	Basic Insulation Level
BSL	-	Basic Switching Impulse Insulation Level
CB	-	Circuit Breaker
CFO	-	Critical Flash Over
DC	-	Direct Current
DSO	-	Digital Storage Oscilloscope
EHV	-	Extra High Voltage
FACTS	-	Flexible Alternating Current Transmission System
GDP	-	Gross Domestic Product
GMSG	-	Gua Musang
GPIB	-	General Purpose Interface Bus
GWh	-	Giga Watt Hour
HFIM	-	High Frequency Inductance Meter
HFT	-	High Frequency Test
HPO	-	High Phase Order
HPRTC	-	High Phase Reengineered Transformer Converter
IVAT	-	Institute of High Voltage & High Current
KKRI	-	Kuala Krai
LFT	-	Low Frequency Test
LOV	-	Lightning overvoltage
MLAGF	-	Multi-layered air gap ferrite
MW	-	Mega Watt
MVA	-	Mega Volt Ampere

PC	-	Personal computer
PDU	-	Protective Device Unit
pu	-	Per unit
ROW	-	Right-of-Way
SDPTLM	-	Scaled-Down Power Transmission Line Model
SLOMCIR	-	Single-layered open magnetic circuit cylindrical iron rod
SOV	-	Switching overvoltage
SPTL	-	Six-Phase Transmission Line
TCPS	-	Total capacitance per segment
TNB	-	Tenaga Nasional Berhad
TOV	-	Temporary overvoltage
TWh	-	Terra Watt hour
USB	-	Universal Serial Bus
US	-	United State

LIST OF SYSMBOLS

a_{ch}	-	The largest dimension of core, m
A	-	Cross section area, m^2
A_e	-	Cross section area of core, cm^2
A_g	-	Cross section area of air gap, m^2
λ	-	Flux linkages, weber-turn
B	-	Magnetic flux density, weber/m^2
C	-	Capacitance, Farad
C_b	-	Base capacitance, Farad
cm	-	Centimetre
Δ	-	Type of transformer connection (delta type)
D	-	Diameter, meter
D_{eq}	-	Diameter equivalent, meter
F/m	-	Farad per meter
G	-	Conductance (leakage resistance), siemens
γ	-	Propagation constant
H	-	Magnetic field intensity, ampere-turn/meter
Hz	-	Hertz
H/m	-	Henry per meter
I	-	Current, ampere
I_b	-	Base current, ampere
I_C	-	Charging current, ampere
k	-	Skin correction factor
Kv	-	kilovolts
Kva	-	kilovoltampere
L	-	Inductance, henry
L_b	-	Base inductance, henry

L_{int}	-	Internal inductance, henry
l	-	Length, meter
l_e	-	Length of the rod (core)
l_{fe}	-	Equivalent length of the flux path, meter
Ω	-	Unit of resistance, ohm
Nf	-	nanofarad
Pf	-	picofarad
P_h	-	Heat dissipation
q^+	-	Positive charge
q^-	-	Negative charge
R	-	Resistance, ohm
R_{AC}	-	AC Resistance
R_{DC}	-	DC Resistance
rms	-	root-mean-square
r	-	Radius, meter
ρ	-	Resistivity, ohm meter
S_{Load}	-	Apparent power, MVA
S_b	-	Base apparent power, VA
S/m	-	Siemens per meter
T	-	Temperature coefficient, ^oC
μF	-	Micro Farad
μF/km	-	Micro Farad per kilometer
μ_r	-	Relative permeability
V	-	voltage
V_b	-	Base voltage
V_{HV}	-	High voltage input
V_{LL}	-	Line-to-line voltage
V_{LG}	-	Line-to-ground voltage
V_{MAX}	-	Maximum voltage
V_{LV}	-	Low voltage output
X_C		Inductive Capacitance
X_L	-	Inductive reactance
ω	-	Angular frequency, rad/sec

Y	-	Admitance
Y_b	-	Base admitance
Z	-	Impedance, ohm
Z_b	-	Base impedance, ohm
Z_{Load}	-	Load impedance, ohm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The transmission line is part of an electric power system network. It serves to transfer electric energy from generating units located at various locations to load centres via the distribution system. The transmission lines also interconnect neighbouring utilities which permits not only economic dispatch of power within regions during normal conditions, but also the transfer of power between regions during emergencies (Saadat,1999).

The increasing demand for power, coupled with the difficulty in obtaining new rights-of-way, the electric power utilities are often faced with the challenge of increasing power transfer capabilities using the existing transmission lines. Beside the cost of development of new transmission line project is high, other reason responsible for the slow increase of transmission is the growing difficulty in getting permits for new lines. Hence, that reason dictates the feasibility of upgrading the capacity of the existing lines. In upgrading the capacity of a line, the possible options among others include installing larger conductors on existing structures, increasing the operating voltage, increasing operating temperature, increasing the reliability, or a combination of above (Rural Utilities Service, 1984). However, they typically involve one or more conditions that exceed the original design capabilities of the existing electrical and structure aspects. An upgrading involves increased mechanical loads or electrical insulation clearance, a number of factors should be considered that can minimize the extent of modification (Simpson, 1990).

1.2 Research Background

Malaysia is a developing country where initially its economy is primarily depending on agriculture, but now industrial activities have contributed more to the economy. Through the “Malaysia Incorporated” concept, Malaysia has successfully changed from an agricultural-based economy to an industrial one, within just two decades (Khairul, 2003). For example, from January to August 2008, investments amounting to RM49.8 billion were approved in Malaysia's manufacturing sector. Investments for the first eight months of 2008 have also surpassed the record for the whole of 2007, which was RM33.4 billion (MIDA, 2008). This strategy encourages foreign investor to set up production, assembly and packaging plants in the country to move the manufacturing sector. To promote such import-substituting industries, the government, directly and indirectly, encourages the establishment of new factories and protects the domestic market. The Malaysian government policy is some ways help to develop new automotive factories, electronic or other factories.

Growth prospects for the Malaysian economy remain favorable in 2007, despite uncertainty in the global economic environment. Strong domestic economic fundamentals will enable the economy to grow at 6.0% in 2007 compare 5.9% in 2006 (Ministry of Finance Malaysia, 2007) and remained sturdy with a growth of 7.1% in the first quarter of 2008 (Ministry of Finance Malaysia, 2008). The strongest growth will be from the industry (mainly the manufacturing sector) and the services sectors, attributing shares of expected 54% and 46% to total Gross Domestic Product (GDP) in 2030 respectively (APEC, 2006). The growth in electricity demand is heavily influenced by the strong demand from the industrial sector, which is projected to increase at 5.4% annually over the decade. Electricity demand for the residential sector will also experience strong growth of 4.9% per year due to improving living standards. And electricity demand of Malaysia will be expected to increase by 4.7% per year over the period of concern, to reach 274 TWh in 2030 (APEC, 2006).

Demands of electric power energy in Malaysia supplied by Tenaga Nasional Berhad (TNB) have increased nearly exponentially over the last two decades (TNB, 2000). Table 1.1 shows the statistical data of Sales of Energy by TNB (Jabatan Bekalan Elektrik & Gas Malaysia, 1999 and Suruhanjaya Tenaga, 2005).

Table 1.1: Statistical data of Sales of Energy in GWh

No	Year	Domestic	Commercial	Industrial	Public Lighting	Mining
1	1994	5,006	7,892	15,932	208	93
2	1995	5,800	9,132	18,414	229	81
3	1996	6,655	10,352	20,704	255	68
4	1997	7,203	12,070	24,606	290	76
5	1998	8,516	13,151	24,447	358	68
6	1999	8,507	13,821	27,051	498	64
7	2000	9,093	14,747	29,818	527	69
8	2001	10,315	16,196	30,754	590	67
9	2002	10,939	17,032	31,371	629	64
10	2003	11,765	18,367	33,440	663	56
11	2004	12,530	19,967	35,732	682	54
12	2005	14,365.5	23,858.6	37,835.3	853.9	38.1
13	2006	15,058.7	24,311.7	37,979.4	876.3	41.5
14	2007	16,051.8	26,323.3	39,289.1	926.9	34.4

To meet the ever-increasing demand for electricity, large and larger power stations are being planned, built, and commissioned for efficient utilization of hydropower and conventional fuel. TNB's total installed generation capacity remains at 8,416 MW. It comprises of 6,505 MW thermal and 1,911 MW hydroelectric power plants. With an additional capacity of 2,400 MW from Kapar Energy Ventures, TNB contributes 56.96 per cent of the total installed capacity in Peninsular Malaysia. Table 1.2 shows total sales, maximum demand and installed generation capacity managed by TNB. The maximum power demand in Peninsular Malaysia in 2007 was 13,620 MW, recorded on 8 August 2007. The year-on-year capacity demand growth rate of 4.85% indicates a rise 3.98% from 2006 (TNB, 2008).

Figure 1.1 Peninsular Malaysia Transmission Network
(Adopted from TNB Annual Report 2007, page 138)

As a consequence of the increasing generation capacity, at the same time longer new transmission lines are to be constructed resulting from the increased demand for electrical power, its increased cost and restriction on Rights-of-Way (ROW) and higher transmission efficiency are some of the major reasons for building Extra High Voltage (EHV) lines. The electric power transmission system in Peninsular Malaysia, consists of four transmission levels, 500 kV, 275 kV, 132 kV and 66 kV transmission systems which form an integrated network known as the National Grid as a Figure 1.1.

The National Grid consists of approximately 17,836 kilometers of overhead transmission lines, 741 kilometers of underground transmission cables and 385 substations with transformation capacity of 75,828 MVA (TNB, 2008). The 132kV was introduced in 1963 whilst the first 275kV lines were commissioned in 1971. The 66kV network is slowly being phased out and parts of 132kV network are being relegated to sub transmission lines. The 500kV system as the new backbone of the National Grid constructed from Bukit Tarek to Janamanjung to channel power from the new Janamanjung Power Station and cater for the increasing demand for electricity (TNB, 2002).

Table 1.2: Total Sales, Generation, and Electric Demand

Year	2007	2006	2005	2004	2003	2002	2001
Sales (GWh)	86,545	82,218.8	78,933.4	72,921.4	68,254.3	63,533.6	59,417.4
Generation (MW)	11.514.5	11,464.8	11,497.8	11,137.5	10,854.5	9,383.2	9,148.2
Max Demand (MW)	13,620	12,990	12,493	12,023	11,329	10,783	No Data

1.3 Power Transfer Capability of Transmission Lines

The amount of power on a transmission line is the product of the voltage and the current of transmission system (Walter, 1981 and EIA Report, 2002) as well as the limitation inherent to system constraint such as stability on maximum capacities of substation terminal equipment, circuit breakers, current transformer and etc (Kiessling, F., et. al, 2002). Additional power can be transmitted reliably if there is sufficient available transfer capability on all lines in the system over which the power would flow to accommodate the increase and certain contingencies or failures that could occur on the system. The power transfer capability of the existing power transmission systems commonly is limited by thermal related constraints, voltage related constraints, and system operating related constraints (Jose. R.D and Daniel. C.L., 2003).

1.3.1 Thermal Related Constraints

The thermal related constraints must be given priority aiming to avoid overheating of transmission lines conductor. Overheating of transmission line conductors can produce aluminum annealing (loss of conductor mechanical strength) and excessive sags (violation of minimum conductor-to-ground clearance). For transmission line, it is important to select an adequate maximum allowable conductor operating temperature, which could be related to current rating of conductor. The transmission lines are typically divided into three thermal constraints: a normal operation rating, a long-term emergency rating (4 hours) and a short-term emergency rating (15 minutes). It is possible to increase the power transfer capability of a transmission system by increasing the current carrying capacity of its transmission lines and substation equipment (Jose. R.D and Daniel. C.L., 2003).

1.3.2 Voltage Related Constraints

The over-voltages can cause insulation failure, leading to short circuits and severe corona performance, while under-voltages can produce inadequate operation of equipment and damage of motors at customer’s facilities. The transmission systems are typically limited to two voltage constraints: a maximum operating voltage equals to 105% of the nominal voltage and a minimum operating voltage equals to 95% of the nominal voltage. It is possible to increase the power transfer capability of a transmission system by increasing the operating voltage within a voltage class, by controlling reactive power flows and consequently reducing voltage drops, and by increasing the operating voltage of its transmission lines and substation equipment (Jose. R.D and Daniel. C.L., 2003).

1.3.3 System Operating Related Constraints

It is necessary to limit the active and reactive power transfers to avoid problems of transient instability, steady-state instability and voltage instability. These are some of the usual transmission systems operating related constraints. These constraints can be alleviated by using the following resources: changing connections of lines at substations, inserting switching stations along transmission lines, installing series capacitors and phase-angle regulators in transmission lines, using small inertia generators and distributed generation, installing Flexible Alternating Current Transmission Systems (FACTS) devices, taking advantage of automatic voltage regulators and governor control systems, changing from preventive operating procedure to corrective operating procedure (Jose. R.D and Daniel. C.L., 2003).

1.4 Six-Phase Conversion Transmission Line

There are several practical and theoretical alternatives for increasing the amount of power transmitted through the existing transmission line circuits are as follows (Simpson, 1990) (El-Marsafawy, 1991)(Woodford, 1975)(Grant, 1982):

a) increase the voltage line,
b) increase the current line,
c) addition of series and shunt compensation, and
d) three-phase to six-phase conversion of three-phase double-circuit transmission line.

There are many factors in considering the alternatives for increasing power transfer capability, the major factors are (Cluts, 1974): power to be transmitted, clearance required for the voltage selected and clearance available on existing structures, mechanical capability of existing structures, and economics of various alternatives. Increasing voltage involves modifying both electrical and structural aspects of an existing line. The first electrical consideration is the need for the increase ground clearance due to longer insulator strings and higher voltage. Consequently, the conductor attachment points need to raises and increase conductor tension. Raising conductor attachment points requires extensive structure modifications. For the increasing current line by means of increasing conductor size or number of conductors and retaining the same voltage does not change the electrical parameters but existing structural capacity should be considered (Hanson, 1991). These two methods are not economical due to time constrain and the requirement of new equipment at the substation.

Due to the reasons described in Section 1.3, consideration of the fundamental limits on power transfer capability in restricted rights-of-way (ROW) led to a concept of increasing the number of phases in a transmission line system circuit known as High Phase Order (HPO). The concept of six-phase transmission lines was introduced by Barns & Barthold (Barthold, 1972). This concept involves the conversion of existing three-phase double-circuit system to six-phase single-circuit system. The six-phase system is accomplished by installing phase transformers converter at both sending-end and receiving-end substations. This concept is a cost-effective and minimum time in implementation compared to the increase system voltage because reconfiguration is located only at the sending and receiving substation without require tower or tower insulator modification. One of the main advantages of six-phase transmission is that a six-phase line can carry up to 73% more electric power than a three-phase double-circuit line on the same transmission ROW (Guyker, 1978), without changing the transmission towers and insulation tower. For this reason, the current research has been carried out to have a better picture and clearer understanding of the six-phase power transmission system.

1.5 Problem Statement

At present if additional power is required in an area, power utilities must add more power lines. Unfortunately in order to add additional power lines, additional rights-of-way (ROW), and land used to hold power transmission structures must be purchased to support the additional power transmission towers. The power transferability of an existing three phase double-circuit transmission line can be increased by upgrading the existing transmission voltage or by converting it into a six-phase single-circuit line. However, both methods the conversion and voltage upgrading will have impact among other on the insulation of the tower and substation equipment (transformer, switchgear) at both ends of the line.

The conversion of three phase double-circuit transmission line into six-phase single-circuit line is chosen because the conversion is located only at both sides of substation. It is utmost important to consider construction to be done within a reasonable length of time as well as location of work, since the power transmission capacity of the line would be discontinued during the reconfiguration works.

Tests on the actual line settings and topology which are part and parcel for this study are the utmost challenges to researchers who have limited access to the lines. It will be more challenging especially reconfiguration exercises for conversion of three phase to six phase system. This is due to the fact that as the continuous and quality of supply is of utmost importance to utilities. Any changes to the actual line settings and configurations while the systems is running at normal is not appreciated by power utilities who are committed to minimizing causes for any interruption to supply system. The problem being addressed by this research can be stated as follows:

“To design, simulate and develop a prototype of a Scaled-Down Power Transmission Line Model (SDPTLM) of three-phase double-circuit TNB transmission network for existing insulation adequacy assessment before actual line is converted into the six-phase system”.

1.6 Research Objective

This research is aimed to conduct a feasibility study for six-phase conversion of the three-phase 132 kV double circuit TNB transmission line. The conversion into a six-phase system is affected by interfacing both end of the line with phase conversion transformers. The research work will accomplish by modeling, simulation and laboratory experimental studies.

If the 132 kV three-phase double-circuit system converted to six-phase system with same operating voltage, the voltage between any two adjacent phases, between any phase and the ground of six-phase system will be 132 kV while it will be the maximum i.e. 264 kV between some of the nonadjacent phases. Thus, potential field distribution on the insulators, tower members, line conductors, transformer conductors and bushings will be substantially different from those in the 132 kV three phase mode. Hence the evaluation of insulation strength for the high phase order conversion is so necessary. The evaluation study is based on the following:

i. To study on the insulation dependent phenomena/criteria such as critical flash over voltage, Basic Switching Insulation Level (BSL) and switching surge impacts.
ii. To conduct modeling and simulation study on the insulation strength of the conversion three-phase to six-phase transmission line under steady state power frequency and switching transient condition.
iii. To develop of a prototype of a six phase transmission line by using “scaled down” concept (operating voltage, tower size, insulator dimension, etc).
iv. Testing on the prototype which will be subjected to scaled down operating voltage applying at its sending end with 2.887 kV phase-to-grond (equal to 5 kV line-to-line of three-phase system) magnitudes of AC voltage.
v. To determine the adequacy of existing insulation strength under steady state and switching transient condition for six-phase conversion.

1.7 Scope of Work

One of TNB Transmission Line networks was chosen that forms the basis of the research model. The line chosen was the 132kV three-phase double-circuit transmission line between Gua Musang and Kuala Krai, Kelantan with a line length of 113.1 kilometres to be converted into six-phase single-circuit network.

The scope of this research work includes the following;

1. Computer simulation.
2. Development of prototype SDPTLM
3. Test on the prototype
4. Comparison of simulation and experimental results

1.8 Thesis Organisation

The thesis consists of seven chapters; Chapter 1 presents research background, general introduction to transmission line, and objectives of this work. Chapter 2 describes general overview of power system in Malaysia, overhead line parameters, modeling method of transmission line and stress on the insulator. Chapter 3 describes the literature survey and previous works of six-phase transmission line. Chapter 4 describes the methods used to simulate the six-phase system. The simulation start from gathering the information of line parameters included tower dimension to building the models in ATP are described. Chapter 5 introduces scaling electrical parameter using per unit method. The simulator components for the line models with the inclusion of inductor verification and calibration test are described. Chapter 6 presents experimental results. Chapters 7 presents summary of the results, discussion, the conclusions and suggestion for further research.