FORMULATION OF MAXIMUM VOLTAGE INDEX FOR POWER DISTRIBUTION SYSTEM CONTAINING GRID-CONNECTED PHOTOVOLTAIC SYSTEM

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DEDICATION

This thesis is dedicated to my father, who constantly support me financially until I finish my master study in UTM. It is also dedicated to my mother, who encourage me not to give up in a difficult time because there is a rainbow after the rain.

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ABSTRACT

Solar energy is one of the favourite renewable energies in Malaysia due to its relatively consistent power generation throughout the year. The solar panel price drops drastically compared to the last few decades, making it affordable to the public. In Malaysia, the government has introduced Feed-in-tariff (FiT) and Net Energy Metering (NEM) to catalyse renewable energy generation, mainly through solar energy. However, high penetration of solar energy has caused several electrical issues such as voltage fluctuation and the protection system's incoordination. In this research, the voltage stability of a bus in a distribution system containing photovoltaic systems are investigated by the concept of power flow of two bus model. The severity of reverse power flow in a distribution system is determined by the proposed index named Maximum Voltage Index (MVI). The main objectives of this report are to formulate a maximum voltage index that can predict the proximity to the maximum voltage of a bus due to reverse power flow from the photovoltaic generator; to validate the validity of the formulated index by using ETAP software; to analyse the voltage collapse event in radial type distribution power system due to reverse power from photovoltaic systems. The results show that MVI is able to predict maximum voltage event of distribution system satisfactorily. Hence, an early correction action can be taken to rectify the situation. Lastly, MVI can be a useful indicator to predict maximum voltage and voltage collapse event for researchers as well as regulatory body.

ABSTRAK

Tenaga suria adalah salah satu tenaga boleh diperbaharui gemar di Malaysia kerana penjanaan tenaga yang agak konsisten sepanjang tahun. Dimaklumkan bahawa harga panel suria turun secara drastik berbanding beberapa abad yang lalu, menjadikannya mampu dimiliki oleh orang ramai. Di Malaysia, pemerintah telah memperkenalkan *Feed-in-tariff* (FiT) dan *Net Energy Metering* (NEM) sebagai pemangkin kepada penjanaan tenaga boleh diperbaharui, terutamanya melalui tenaga suria. Walau bagaimanapun, penembusan tenaga suria yang tinggi telah menyebabkan beberapa masalah elektrik, seperti ketidakstabilan dan penyelarasan sistem perlindungan. Dalam penyelidikan ini, kestabilan voltan bas dalam sistem pengedaran yang mengandungi sistem fotovoltaik disiasat oleh konsep aliran daya dua model bas. Keterukan aliran daya terbalik dalam sistem pengedaran ditentukan oleh indeks yang dicadangkan bernama Maximum Voltage Index (MVI). Objektif utama tesis ini adalah untuk merumuskan indeks voltan maksimum yang dapat meramalkan jarak dengan voltan maksimum bas kerana aliran daya terbalik dari penjana fotovoltaik; untuk mengesahkan kesahihan indeks yang dirumuskan dengan menggunakan ETAP; untuk menganalisis kejadian kejatuhan voltan dalam sistem kuasa pengedaran jenis radial kerana daya terbalik dari sistem fotovoltaik. Hasil kajian menunjukkan bahawa MVI dapat meramalkan kejadian voltan maksimum sistem pengedaran dengan memuaskan. Oleh itu, tindakan pembetulan awal dapat dilakukan untuk memperbaiki keadaan. Terakhir, MVI boleh menjadi petunjuk berguna untuk meramalkan kejadian kejatuhan voltan dan voltan maksimum bagi penyelidik dan juga badan pengawal selia.

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LIST OF ABBREVIATIONS

ETAP	-	Electrical Transient Analyzer Program
FACTS	-	Flexible AC Transmission System
FVSI	-	Fast Voltage Stability Index
IEEE	-	Institute of Electrical and Electronics Engineers
LVSI	-	Line Voltage Stability Index
MPPT	-	Maximum Power Point Tracker
MVI	-	Maximum Voltage Index
NVSI	-	New Voltage Stability Index
PV	-	Photovoltaic
SVC	-	Static VAR Compensator
VCPI	-	Voltage Collapse Point Indicator

LIST OF SYMBOLS

δ	-	Voltage Angle
θ	-	Line Impedance Angle
Z	-	Line Impedance
R	-	Line Resistance
X	-	Line Reactance
I	-	Current
S_r	-	Apparent Power at Receiving Bus
P_r	-	Real Power at Receiving Bus
Q_r	-	Reactive Power at Receiving Bus
V_r	-	Voltage at Receiving Bus
V_s	-	Voltage at Sending Bus
L_{mn}	-	Line Stability Index

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CHAPTER 1

INTRODUCTION

1.1 Grid-Connected Renewable Energy Distributed Generation

The utilisation of electrical energy had driven the second industrial revolution, which replaced the first industrial revolution in the mid of 19th century. Since then, electrical energy becomes the most important form of energy in the modern society. The conventional electrical power generations using brown energy sources such as coal, oil and natural gas involve greenhouse gas emissions. Although fossil fuels are abundantly available and highly reliable, its negative impacts to the environment cannot be ignored because it is unsustainable. Green energy, as opposed to brown energy, is defined as energy derived from self-sustaining energy sources. Examples are solar energy, tidal energy, geothermal energy, wind energy and biomass energy.[1] The combustion of fossil fuel releases greenhouse gas causing global climate change and it is one of the main factors of global warming along with other factors like deforestation and increasing livestock farming. In order to curb climate change due to excessive greenhouse gas emission, green energy is introduced to replace brown energy as it is sustainable and environmentally friendly.

According to [2], renewable energy capacity grows steadily over years. It is believed that this trend keeps growing at an accelerated scale. Solar energy is the frontrunner in term of annual additions of renewable power capacity. Therefore, high penetration of renewable energy is expected in power systems.

The main factor of rising numbers of solar photovoltaic is falling of cost. Low price of solar photovoltaic panel has made the solar power more competitive to the other types of renewable energies. In the US, it is reported that residential solar photovoltaic system cost reduced 63% from 2010 to 2018. Around 57% of the reduction is due to a decrease of hardware cost. On top of that, soft cost like labour cost and tax also dropped considerably. Additionally, commercial solar photovoltaic system cost plummeted 66% from 2010 to 2018. The main contributor for the reduction is a decrease of hardware cost which allocate 79% of the reduction [3].

High penetration is often associated with reverse power flow. Reverse power flow occurs when the power generated from renewable distributed generators exceed the local power demand. Consequently, the excessive power flow into the grid in opposite direction to normal. This occurrence can be explained by the intermittent characteristic of renewable energies as renewable energies generation are highly dependent on ambient conditions such as temperature and solar irradiation for solar photovoltaic system and wind speed and air density for wind turbine. Distributed renewable energy generators cause incoordination of the electrical protection systems because fault level current is changed depending on the degree of reverse power flow and the model of generators. [4]

In addition, voltage imbalance occurs due to non-uniform distribution of distributed generators to the utility grid. During off-peak period, voltage rise of electrical system occurs due to excess power injection. The voltage rise may violate the voltage upper limit set by the utility company. In [5], more technical challenges are mentioned such as voltage regulation, line overloading, flickering and harmonics. Many literatures studied and proposed solutions to counter the above-mentioned issues. [6] stated the importance of minimisation of imbalanced voltage and present mathematical model and algorithm to reduce voltage imbalanced. In [7][[8], they showed that active power and reactive power have direct relationship with voltage profiles in radial type distribution system. The effect of distributed generations on power quality is investigated by[9]. Literature in [10] addressed that traditional structure of power system which the system is designed for one-way flow of power are greatly affected by high penetration of distributed photovoltaic system in term of voltage regulation mechanism.

1.2 Indices and Solutions to Address Stability Issue of Power System

Voltage magnitude alone is not sufficient to determine the status of a power system. Authors in [11] propose L-index of load buses for the determination of Static VAR Compensator (SVC) placement deriving from static voltage stability analysis. The higher the index, the more instable of the bus. The proposed methodology has been shown effective on customized network and a practical 24 bus extra high voltage power system. A new approach called Revamp Voltage Stability (RVSI) Indicator was proposed by [12]. RVSI is derived from the equation of current flow through sending end and receiving end of 2 bus system. By using the index, level of vulnerability of the system can be acquired. It can be used for placement determination for both distributed generation and SVC. The index is tested under IEEE 14 bus system with 1.8 times of base loading to simulate heavy loaded situation. The approach successfully reduces the index after SVC and distribution generation placing at the weak bus determined by the approach.

Another innovative method was proposed by [13], where the voltage of the power system is regulated by combined SVC and PV inverter. When the voltage falls below the limit, the inverter injects reactive power into the grid according to its rating to rise the output voltage, while the voltage is higher than the limit, the inverter absorbs reactive power, but this is limited because the inverter cannot absorb reactive power more than its rating. In this situation, SVC take place to absorb the reactive power. However, the inverter cannot take the role as a voltage regulator like in the day time because no power harvested from the sun, unless battery bank is considered.

Proper placement of distributed generation (DG), SVC and capacitor banks is critical and emphasised by many researches. Many researchers develop algorithms and various indexes as the methods to analyse the best placement of DG and SVC. In [14], the authors use genetic algorithm to find out the best location to place SVC in 33/11kV distribution substation with eleven buses, containing two power transformers with 3MVA and four distribution transformers with four static loads. Genetic Algorithm (GA) is an optimization algorithm inspired by biological principles of evolution. GA randomly samples the whole design space and then ameliorate the found design point by employing genetics-based principles and probabilistic selection criteria. The other searching algorithm is Particle Swarm Optimisation (PSO) which is used in [15]. The algorithm is motivated by the activities of bird flock to search for food. In the searching process, the algorithm generates a group of random particles to search for the best fitness value. The result of the literature shows that placing distributed generation and SVC at the right place and identifying the optimal size can remarkably enhance the voltage profile. It is also revealed that DG is better in loss reduction compared to SVC. The best side of PSO is that few and no assumption have to be made but it does not guarantee an optimal solution can be found.

1.3 Roles of FACTS in Power System Research Goal

A Static VAR Compensator (SVC) is a type of Flexible Alternating Current Transmission System (FACTS) device, which utilises power electronics like Thyristor to control the reactive power flow in a power system. The reactive power from SVC is adjusted to control parameters of power system such as voltage level. SVC contains reactor bank and capacitor bank and their current are controlled by the thyristors.

There are four main types of SVC, namely Thyristor controlled reactor (TCR), fixed capacitor thyristor reactor (FC-TCR), thyristor switched capacitor (TSC) and thyristor-controlled reactor-thyristor switched capacitor (TCR-TSC). TCR is connected to thyristor in each phase. Reactive power is adjusted by controlling the current through the reactor by using the thyristors. FC-TCR combined TCR and fixed capacitor bank. This type of SVC is often used in sub-transmission and distribution system. TSC contains a shunt capacitor bank and it is divided into several branches. Each branch is independently switched on or off through anti-parallel connected thyristors. TCR-TSC is a combination of TCR and TSC. The advantage of this type SVC is that it can provide a smooth reactive power control at very wide range due to both capacitor bank and reactor bank are fully under control.

The benefits of FACTS device are stated in [16] and FACTS have been shown to be a viable solution to improve the performance of a power system. Based on the

IEEE definition, SVC is a shunt connected static var generator or absorber which is able to adjust its output reactive power to maintain or control specific parameters of electrical power system like bus voltage, frequency and others. SVC employs power electronics such as thyristor to control its output reactive power flow for voltage regulation, reactive power control and transient stability improvement of the system. Moreover, integrating SVC with existing power system reduces the number of new facilities needed as it extends the loadability of existing power system.

1.4 Voltage Stability of Distribution System

In this report, voltage stability of distribution system is the main topic to be discussed. Voltage stability is defined as the ability of the power system retain the voltages within statutory limits. In Malaysia, the maximum voltage fluctuation allowed due varying solar radiation is 6% for both low voltage and medium voltage system.[17] In recent years, voltage stability of distribution system becomes the concern of power system planners and researchers due to rising numbers of grid-connected distributed generation because instability of voltage will lead to voltage collapse.

In Malaysia, the number of renewable energy distributed generation is increasing over the years and this can be attributed to Feed-in Tariff (FiT) and Net Energy Metering (NEM) schemes which promote utilisation of renewable energy in the public. There are several types of devices used in voltage regulation, namely On-load tap changer (OLTC) and static var compensator. OLTC regulates voltage levels by changing number of turns in the one winding of a transformer. Thus, different ratio of the transformer generates different level of voltages [18].

1.5 Problem Statement

The rising number of distribution generations in power system post many technical challenges to power engineer as well as utility companies. One of the most challenging issues is voltage instability due to reverse power flow from renewable distributed generations. The intermittent nature of renewable power generation makes the issue more complicated.

The voltage stability of distribution system needs to be assessed and the problem needs to be mitigated promptly. Otherwise, cascading breakdown of power generation may occur and this may lead to total blackout or severe voltage collapse. Although existing voltage stability indices have been developed to determine the point of voltage collapse in transmission system, to my knowledge, there are no voltage stability indices are proven effective for use in radial type distribution system. Some of the indices' assumptions are not suitable for radial type distribution system have yet to be demonstrated. For example, Line stability factor (LQP) index developed by making an assumption of line reactance is greater than line resistance is not a common case for radial type distribution system since radial type distribution system has higher resistance to reactance ratio. This can be explained by the length of line in distribution system is much shorter than transmission system while line reactance is the function of line length, and geometry arrangement of transmission cables. Next, an index called Fast Voltage Stability Index (FVSI) assumes the voltage angle between sending bus and receiving bus is zero. This assumption is not applicable for radial type distribution system containing high reverse power flow because the voltage angle between sending and receiving bus is large. Therefore, the formulation of a Maximum Voltage Index (MVI) for use in radial type distribution system is required.

1.6 Research Objective

In light of a large magnitude of reverse power flow from the increasing number of photovoltaic generations, an approach to determine the voltage stability of the system is critical. The research goal is to formulate a suitable index to predict the voltage stability for a radial type distribution system which contain distributed photovoltaic generations.

The primary goal of this study is to predict maximum voltage occurrence in distribution system due to reverse power flow from distributed photovoltaic generation. Several objectives are needed to achieve the goal and they are as follows:

(a) To formulate an index that can predict the proximity to maximum voltage event of a radial type distribution power system

(b) To validate the validity of the formulated index by using ETAP software

(c) To analyse the voltage collapse event in radial type distribution power system due to reverse power from photovoltaic systems.

1.7 Research Scope

The research work focuses on the prediction of maximum voltage occurrence and voltage collapse in distribution system due to reverse power flow. MVI is verified on IEEE 33-bus 12.6kV radial type distribution. The simulations are carried out by using Newton Raphson method in Electrical Transient Analyzer Program (ETAP) 12.6.0 and results are plotted by Microsoft Excel 2019.

1.8 Report Organisation

Chapter one introduces a brief background of technical challenges and current solutions to tackle the problems. Challenges brought by photovoltaic system in term of voltage stability and the motivation of the research work are also discussed in the chapter. Chapter two gives an overview of power system stability and a review of voltage stability indices. Next, chapter three focuses on the formulation of MVI that being proposed maximum voltage prediction. Chapter four justifies the formulated index with simulation results as well as discussion on the results. Lastly, chapter five concludes the research work and provide suggestions for future works.

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