Faculty of Engineering

VOLTAGE REGULATION MANAGEMENT OF HYBRID DISTRIBUTION SYSTEM

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VOLTAGE REGULATION MANAGEMENT OF HYBRID DISTRIBUTION SYSTEM

MISHABELLE DESSY ANAK ALEX

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ABSTRACT

The increasing potential of renewable energy integration into the existing distribution system, particularly with solar photovoltaic (PV) energy has raised much concern especially in regard to the voltage at the end-user.

Variation of voltage caused by changing solar radiation could lead to varying voltage output where frequent tap changes occur in the voltage regulators such as on-load tap changer transformer. There is a need for a more efficient method of voltage regulation since the mechanical switches of existing on-load tap changers are now a liability due to the frequent tap changes.

The main objective of this work is to design a Simulink model for a solid-state on-load tap changer autotransformer using MATLAB environment. In the soft switching approach, thyristors act as the main switching component for the tap changer, replacing the mechanical switches to switch taps of the autotransformer windings in response to voltage variation.

This method involves validation using small-sized hardware such as Arduino UNO microcontroller where the proposed design will be evaluated by comparing regulated output voltage with the standard system voltage as well as monitoring the tap change operation during different conditions such as normal and abnormal condition. The resulting design of the solid-state on-load tap changer is found to be more efficient in comparison to a mechanical on-load tap changer in terms of tap change and selection speed as well as arcing elimination. The OLTC was able to detect voltage changes within each tap range and in response select the proper tap from nominal tap, optimising the voltage output to 1.0 pu ±0.024pu variation. The solid-state tap changer reduces time of tap selection by 83% in comparison to mechanical tap changers with 1.0s switching duration.

ABSTRAK

Potensi peningkatan integrasi tenaga boleh diperbaharui ke dalam sistem pengagihan sedia ada, terutamanya dengan tenaga solar photovoltaic (PV) telah menimbulkan kebimbangan terutamanya berkaitan voltan pada pengguna akhir.

Variasi voltan yang disebabkan oleh perubahan sinaran suria boleh membawa kepada output voltan yang berbeza-beza di mana perubahan *tap* kerap berlaku dalam pengawal voltan seperti *on-load tap changer* transformer. Terdapat keperluan untuk kaedah pengawalan voltan yang lebih cekap kerana suis mekanikal *on-load tap changer* sedia ada kini menjadi liabiliti disebabkan oleh perubahan *tap* yang kerap.

Objektif utama kerja ini adalah untuk mereka bentuk model Simulink untuk autotransformer *on-load tap changer* semikonduktor menggunakan persekitaran MATLAB. Dalam pendekatan pensuisan lembut, thyristor bertindak sebagai komponen pensuisan utama untuk penukar *tap*, menggantikan suis mekanikal untuk menukar *tap* belitan autotransformer sebagai tindak balas kepada variasi voltan.

Kaedah ini melibatkan pengesahan menggunakan perkakasan bersaiz kecil seperti mikropengawal Arduino UNO di mana reka bentuk yang dicadangkan dinilai dengan membandingkan voltan keluaran diregulasi dengan voltan sistem standard serta memantau operasi penukaran *tap* dalam keadaan berbeza seperti keadaan normal dan tidak normal. *On-load tap changer* dijangka lebih cekap berbanding *on-load tap changer* mekanikal dari segi penukaran tap dan kelajuan pemilihan tap serta eliminasi fenomena *arcing*. OLTC dapat mengesan perubahan voltan dalam setiap julat pili dan sebagai tindak balas pilih *tap* yang betul daripada *tap* nominal, mengoptimumkan output voltan kepada variasi 1.0 pu ±0.024pu. Penukar *tap* elektronik mengurangkan masa pemilihan *tap* sebanyak 83% berbanding penukar *tap* mekanikal dengan tempoh penukaran 1.0s.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

AC – Alternating Current

ASEAN - Association of Southeast Asian Nations

DC – Direct Current

HV – High voltage

HVDC – High voltage direct current

IGBT – Inverted Gate Bipolar Transistor

I/O – Input/output

IOT – Internet-of-Things

LED – Light emitting diode

LV – Low voltage

MATLAB - MATrix LABoratory

MV – Medium voltage

NDC - Nationally Determined Contributions

OLTC – On-Load tap changer

PV – Photovoltaic

SARES - Sarawak Alternative Rural Electrification Scheme

SSR – Solid-state relay

SSO – Steady-state operation

CHAPTER 1

INTRODUCTION

1.1 Background

In conjunction with Malaysia's target to achieve its Nationally Determined Contributions (NDC) goal in reducing economy-wide carbon intensity (against GDP) of 45% in 2035 in comparison to 2005 level as mentioned at The Special Meeting of ASEAN Ministers on Energy and the Minister of Economy, Trade and Industry of Japan [1], Malaysia is expected to grow its renewable energy sources into the generation mix with more support from the government. Considering Malaysia's climate and natural resources, it is safe to assume that Malaysia will be focusing on solar energy development in the upcoming years. While the decarbonization of electricity generation especially through the development and installation of solar power into power generation will see a decrease in carbon emission in the generation process, the potential of high solar photovoltaic (PV) penetration into the existing power grid raises a concern towards its negative effects towards both supplier and consumer.

Without proper regulation, even in smaller systems like hybrid microgrids, the setbacks from solar power integration can be observed – most especially voltage variations of the power transformer output [2]. In most cases, voltage variation issues in power transformers are significantly reduced by the use of tap changers. These days, On-Load Tap Changers (OLTC) are more commonly used as it the switching operations are conducted under "make-before-break" contact conditions which allow for changing the voltage and winding ratio without experiencing momentary system load loss or short circuit between adjacent taps [3].

With the advancements of semi-conductors, solid-state OLTCs are rapidly developing with the use of different types of semi-conductor devices [4], [5] due to its advantages over mechanical OLTCs.

1.2 Problem Statement

As of recent years, integration of renewable energy into the existing power grid has been more common as part of efforts to reduce carbon emissions from power generation. However, the high penetration of renewable energy into the grid such as solar photovoltaic (PV) has caused concern due to the adverse and unwanted effects on power transformers such as reverse power flow [6] and the variation of transformer output voltage [7]. These power quality issues such as voltage flicker, over and undervoltage provides an unstable voltage at user-end which requires proper mitigation.

In order to overcome fluctuating voltages, mitigation methods such as voltage regulation is applied using the likes of devices such as On-Load Tap Changer (OLTC) among others [8]. For a long time, the mechanical OLTC has been effective in regulating the output voltage of power transformers by increasing or decreasing the voltage as needed. Its low steady-state losses and ability to maintain voltage made it an optimal choice for mitigation of voltage variations. However, the switching operation of the mechanical tap changer causes the contacts to wear down due to sparking/arcing especially if tap operation occurs frequently due to fluctuating voltage, hence reducing its lifetime, and requiring costs for maintenance and replacement [4]. To tackle the issue, the solid-state or electronic OLTC has been developed in order to eliminate the arcing problem and increase performance by ridding the mechanical parts of the tap changer. In this work, the solid-state OLTC design using thyristors as switches is modified for improvements.

Voltage changes and tap operation occur frequently when the power grid is connected with a solar PV source due to the varying solar radiation[2]. For a mechanical OLTC, tap operations are performed manually with the push of a button. Now, with the advancement of solid-state OLTC, voltage variations can be recorded electronically, and all operations are performed by computers. In this project, an Arduino UNO microcontroller will be used to extend the application for real-time use.

1.3 Objectives

In this work, the objectives for this project are:

i) To study the voltage regulation in hybrid power grid with renewable resources

ii) To design partially rated, solid-state assisted on-load tap changing (OLTC) autotransformer

iii) To validate the operation of the voltage regulator/tap changing autotransformer in real-time or experimentally

1.4 Summary

Due to the potential and predicted increase in renewable energy integration into the existing power grid, in particular solar photovoltaic (PV), negative effects towards load-end users such as voltage fluctuations of transformer output voltage are of concern for electric utility providers and operators. Such concerns are caused by the unstable power generation of renewable energy sources due to their changing nature which depends on solar radiation in the case of PV generation. Voltage mitigation methods have been developed for the purpose of regulating the voltage output of transformers such as the likes of on-load tap changers (OLTC) for transformers. For a long period, mechanical OLTCs have been the go-to device for voltage regulation due to its advantages such as low steady-state losses and cost-saving feature. However, the short lifespan of the device due to constant tap changing operation caused by arcing phenomenon has led researchers to venture for an alternate solution. With the advancements in electronic technology, solid-states have become a breakthrough over the past few decades in the development of OLTCs. In this work, we will be focusing on the comparison of several voltage regulation methods and the proposal of an improvement of design of a solid-state OLTC.

Chapter 2

LITERATURE REVIEW

2.1 Overview

The integration of existing Alternating Current (AC) power grids with solar Photovoltaic (PV) powered microgrids causes voltage issues in distribution such as fluctuating or overvoltage due to the uncertain weather and factors such as sunshine exposure and cloudiness [9]. Voltage variation as such may cause unwanted effects at user-end. This chapter will cover the basis of efforts in voltage regulation in power autotransformers by introducing an updated version of solid-state (or electronic) tap changer. Materials and previous publications referred to in the making of this work will be included in this chapter.

2.1.1 Solid-State Tap Changers

The rapid development of semiconductors such as thyristors, triacs and insulated gate bipolar transistors (IGBT) has made way for mitigation of voltage variation problems through the use of semiconductors in voltage regulators. The application of solid-state or electronic tap changers eliminates the issue of arcing and wear-downs by ruling out mechanical complications. Semiconductors and microcontrollers are instead used to determine and control the tap changes for either increasing or decreasing the voltage as needed to compensate for the varying voltage output. Previous works in regulating voltage output of transformers applied the use of solid-state relays (SSR)[10] and back-to-back series-connected IGBTs [4].

2.1.2 Solar Photovoltaic (PV) Energy Potential and Integration in Sarawak

Sarawak is one of the 13 states in Malaysia and has an equatorial climate with two monsoon seasons between November and February, and between June and October. Temperature in the state ranges from 23°C in the morning to 32°C in midday and stays somewhat consistent all year round [11]. This implies that sunshine and solar radiation is abundant given that it is not raining or cloudy, the latter being a major contributor to voltage variation in solar power output voltage as Malaysia on average receives 4 hours of sunshine a day [2]. This, however, should not hinder the efforts to achieve feasible renewable energy in Sarawak as it has been proven possible by multiple projects conducted by the government and Sarawak Energy, an electrical utility company through projects such as SARES in which rural areas yet to be connected to the main power grid due to geographic difficulties benefit from solar-powered electricity [12], [13]. Figure 2.1 below shows the hybrid solar microgrid in Bario successfully built in Bario, Sarawak.

Figure 2.1 Bario hybrid microgrid from Sarawak Energy [13]

While it is entirely possible to provide a steady supply of stand-alone solar PV powered electricity to villages and residential households, the integration of the solar microgrid into the existing power grid may introduce problems. This is because high PV penetration into a traditional grid with the addition of possible heavy loading such as charging of electric vehicles (EV) may lead to adverse unwanted effects such as voltage fluctuations, power fluctuations, and reverse power flow. Reverse power flow occurs when generated power flows from low voltage (LV) network to medium voltage (MV) network due to a large generation of solar powered electricity as opposed to from medium voltage (MV) network to low voltage (LV) network in one direction power flow of a distribution network.

2.1.3 On-Load Tap Changer (OLTC) and the Effects of High PV Penetration on OLTC

On-load tap changer (OLTC) is a mechanism used to regulate the output voltage of a transformer through the tap position by first regulating the turns ratio which, with conductors involved, then regulates the voltage ratio. In theory, the higher the turns, the more conductors are used and the higher the voltage due to the increase in magnetic field. The OLTC is connected to the transformer via the tap windings and maintains an acceptable range of voltage from the output to compensate for the high or low variation in the load. However, with the integration and high penetration of PV system into the existing power grid, the OLTC may expect to work harder to bring back voltage to its normal range due to the voltage variations, leading to high number of tap changes. A previous study also suggests cloud movements may call for frequent operation of the OLTC, wearing down its effectiveness and lifespan [9].

2.1.4 Mechanical On-Load Tap Changer (OLTC)

As the name suggests, mechanical tap changers peruse mechanical switches to perform tap changes to regulate the output voltage of transformers. The mechanical switches are rotated using motors with the push of a button and the taps change step-by-step. The main advantage of using mechanical tap changers is the low steady-state loss and high overload capacity which helps overcome faults during steady-state operations (SSO) [7]. However, the lifespan of the mechanical switch is brief as the constant switching of the contacts of the diverter switches at very high voltage leads to sparking or arcing, and eventually wear and tear. Companies will have to consider the cost of