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Development of Advanced Unbalanced Power Converter for AC-DC Power Distribution System

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ABSTRACT

With the rapid demand of electricity, the installation of power electronics-based equipment in power distribution system has grown rapidly for ac/dc system coupling, system protection, alternative energy source interface, etc. This paper focus on power electronic component and system modelling techniques and three-phase ac/dc power flow analysis for power distribution systems. The research discusses the models that are developed for unbalanced power electronic converters, such as thyristor converters, diode rectifiers, and Pulse-Width- Modulated (PWM) converters. The modelling approach captures the imbalance of distribution systems using three, delta-connected, single-phase converters. To perform system analysis, these models have been incorporated into two types of ac/dc power flow solvers: A three-phase backwards/forward sequential solver and a three-phase unified solver using the modified nodal analysis method. Both solvers have been applied to unbalanced radial and weakly meshed distribution systems. Finally, an ac/dc system hardware test bed was created to validate the proposed models and the performance of the power flow solvers. Extensive hardware tests, time-domain simulations, and steady-state analysis have been performed.

KEYWORDS: *power distribution system, Pulse-Width- Modulated (PWM) converters, AC system, DC system*

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I. INTRODUCTION

Recent developments in power electronics offer the possibility of wide-scale integration of power electronics based devices into power systems [1]. Resulting benefits would include improved control of the delivered power, high energy efficiency and high power density. In order to implement these devices into distribution systems successfully, system wide analysis should be performed in order to understand their impacts on system planning and operation. As such, appropriate mathematical models and application tools, are desired to capture the characteristics of power electronic devices. This paper address three-phase ac/dc power flow analysis for power distribution systems. In power systems, ac/dc conversion using power converters has been developed and installed in transmission systems in past decades [2]. With a focus on power distribution systems, the implementation of power electronic devices has grown rapidly in recent years, such as in terrestrial distribution systems [3], shipboard power systems [4], and transportation systems [5]. For example, adjustable-speed drives are replacing constant speed electric motor-driven systems in industry to improve efficiency by controlling the motor speed. Power electronics have also been used as interface to transfer power from alternative energy sources, such as wind, photovoltaic, into the utility systems. In shipboard power systems, power converters introduce the potential to actively control the coupling of ac/dc systems.

Operated faster than electromechanical devices to open/close circuits and prevent the spread of faults using zonal electrical distribution [4].

II. Literature Review

The installation of these power electronic devices may have either positive or negative impacts on the operation and control of distribution systems. To investigate the impacts of these new devices, it is essential to establish a foundation to investigate their properties and to incorporate them in planning and operation studies. Fundamental tools for power system analysis include component and system modelling and steady-state ac/dc power flow. The models and power flow have been used in many applications in planning and operation, such as protection system design, service restoration, power quality analysis, etc. The applications require appropriate models to reflect the actual behaviour of system components as well as robust and efficient power flow solution algorithms.

Historically in the power industry, the main power electronics applications have been in High Voltage Direct Current (HVDC) systems, solid state VAR compensators, unified power flow controllers, and others. As a result, a number of models were created to handle these devices and implemented in power flow solvers, see for example [6-12]. In HVDC systems, large inductors are installed in the dc systems to smooth dc currents. Thus, many converter models and subsequent power flow formulations assumed the systems to be three-phase with constant dc currents. In [6-9], the network and loads are assumed to be three-phase balanced. In these models, the converter ac currents were assumed to be filtered and had sinusoidal waveforms with low distortion. The current magnitudes were calculated by performing FFT analysis on the tri-state square ac currents before filters. The dc systems were modeled as constant power ac loads in the power flow solvers.

Some three-phase, unbalanced systems, converter models have also been developed for HVDC system analysis. In [10][11], a three-phase thyristor converter model was proposed. The imbalance of systems was captured by the conducting periods of thyristors on each phase. In [12], three-phase thyristor converters were modelled as equivalent sequence regulation transformers using modulation theory. In these

three-phase models, it was still assumed that the dc currents were constant.

In contrast, power distribution systems are inherently unbalanced systems consisting of single, two and three-phase components and subsystems. Also because of limited space [13], often there are not enough filtering devices to eliminate the harmonics generated by power electronic devices. In addition, installation of large dc capacitors amplifies dc current ripples in some distribution system devices, such as Adjustable Speed Drives (ASDs), As such, the Total Harmonic Distortion (THD) in the dc currents and ac currents could be much higher, e.g. THD is among 40-60% for ASDs [13], than those in HVDC systems. For these reasons, the previous modelling approaches and power flow solvers for HVDC system analysis are not directly applicable to power distribution systems. New modelling techniques are desired to capture the properties of the power electronic devices and to be implemented in distribution system analysis tools.

Furthermore, these new mathematical models and analysis tools should be tested and validated in real-life environments. It is noted that real system data is not always accessible and it is also impractical to perform experiments on real systems for the sole purpose of validation. As such, it is desired to develop scaled-down, flexible, ac/dc system hardware test beds.

Sequential power flow solvers were first developed in the 1970's [8] for HVDC system analysis. In the past three decades, various sequential solvers have been proposed for balanced and unbalanced [11] HVDC systems. Since HVDC systems are typically balanced, power flow equations were established using single-phase component models [12]. In unbalanced power flow solvers, three-phase converter models were proposed with constant dc currents. In the above solvers, the ac power flow was solved using either the Newton-Raphson method or fast decoupled Newton methods[13]. The dc power flow was solved using either the Gauss-Seidel method [14] or the Newton method[15].

III. Model of AC/DC system:

A three-phase sequential power flow solver is proposed. The power flow equations are solved successively between ac systems and dc systems. In this proposed method, while solving ac power flow, the dc system is represented as equivalent delta-connected ac components on the converter ac buses. While solving dc power flow, the ac systems are represented as equivalent dc components on the converter dc buses.

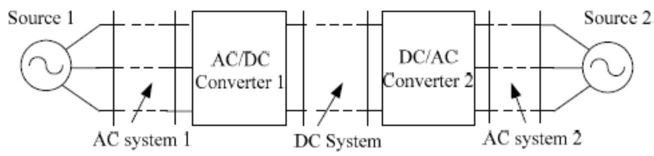

Figure .1ac/dc system

IV. Advanced three phase model

In order to develop three-phase ac/dc power flow solvers, appropriate ac and dc component models are desired. In this thesis, three-phase models from [29] are used for ac transformers, distribution lines, switches, and loads. For dc components, distribution lines and switches are modelled using pure resistances. DC loads are treated as constant resistance (Z), constant current (I), and constant real power load (P), or linear combination ZIP loads. The dc inductance and capacitance in the dc filters are considered in the converter models. The ac and dc systems are interconnected with various types of converters. Since the ac and dc power flow are solved separately in the sequential solver, equivalent power flow components have been developed to decouple the ac and dc systems. Depending on the converter's types, various equivalent components are built using the unbalanced delta-connected converter models. In the ac systems, the dc systems are modelled as delta-connected ac loads for rectifiers and sources for inverters on the converter ac buses. In the dc systems, the ac systems are modeled as dc sources for rectifiers and loads for inverters on the converter dc buses. The parameters of the equivalent ac and dc components depend on the converter models and the previous power flow solutions. For example, Figure 2 shows the Decoupled ac and dc systems used in the sequential power flow solver

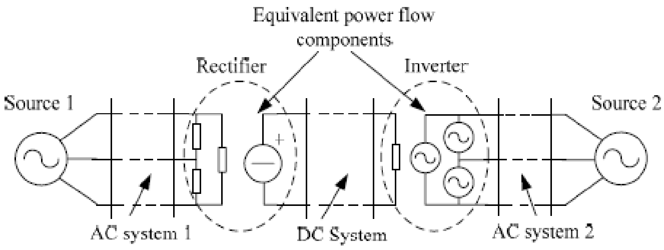

Figure.2 Decoupled ac and dc systems used in the sequential power flow solver

Figure 3.shows an ac/dc system with five converters. There are two ac subsystems and three dc subsystems. The operating modes of the converters and the power flow directions are shown in the figure.

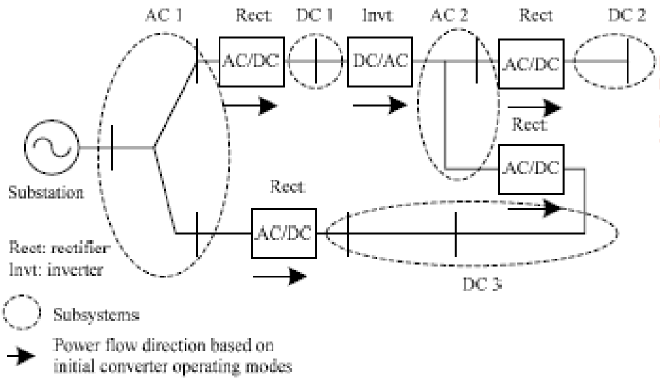

Figure. 3 The one-line diagram of a sample ac/dc system with 5 subsystems

V. Results & Conclusion

The power flow algorithm was programmed in MATLAB. It was tested on a 1.5 GHz, 1024 MB computer for bi-directional power flow studies in a three-phase 12-bus system shown in Figure 3.6. Bus 1 is the main source bus and the network contains:

- A three-phase back-to-back thyristor converter placed between ac bus 4 and dc bus 7, allowing currents to flow in both directions.
- A three-phase PWM converter placed between ac bus 9 and dc bus 8
- Five ac constant impedance loads and one dc constant impedance load
- A Distributed Generator (DG) placed on bus 11.

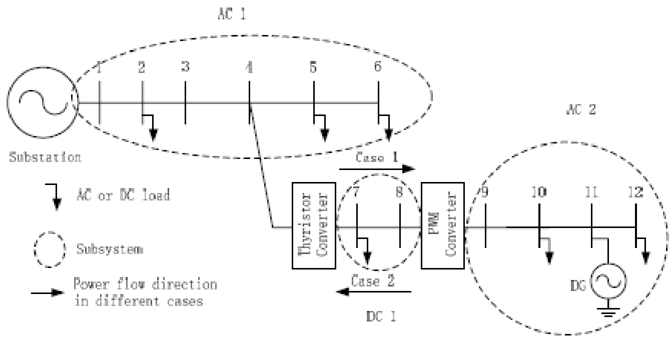

Figure 4 A one-line diagram of the 12-bus AC/DC system

A three-phase sequential power flow solver was developed for ac/dc power flow studies. The three-phase delta-connected converter models proposed in Chapter 2 have been incorporated in the sequential solver to model three-phase converters under unbalanced operating conditions. In order to determine the sequence for solving power flow, a ranking method was proposed to rank the subsystems. The ac/dc power flow was solved using a backward/forward algorithm based on subsystem ranks.

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