MODELLING AND CONTROL OF UPFC FOR POWER FLOW MANAGEMENT

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Abstract
This paper discusses control of Unified Power Flow Controller (UPFC) to improve power system voltage stability. With its unique capability to control parallel real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it impact on power system stability.This will give the power system operators much needed flexibility in order to satisfy the requirement that the deregulated power system will impose. The basic control method of UPFC is such that the shunt converter controls the transmission line reactive power flow and the dc-link voltage. The real power flow in the transmission line and the UPFC bus voltages are controlled by series converter. In this paper the performance of UPFC is analyzed to control the flow of power over the transmission line. In the absence of UPFC, real power, reactive power and voltage through the transmission line cannot be controlled. The circuit model for UPFC is developed using rectifier and inverter circuits in MATLAB/Simulink and simulation results are presented to validate the model.
Index Terms: FACTS, Shunt Converter, Series Converter, UPFC

I. INTRODUCTION

Modern power grid contains of complicated networks where several generating stations and load centers are interconnected through long power transmission and distribution networks. Utility distribution networks, crucial industrial operations and sensitive industrial loads all suffer from numerous varieties of outages and interruptions which may result in significant financial loss, loss of production, idle work forces etc. Nowadays due the ever-changing trends and restructuring of power systems, the customers are trying forward to the quality and reliability of power supply at the load centers. A power quality problem is an incident manifested as a nonstandard voltage, current or frequency that ends up in a failure or a maloperation of end use equipments. With modern trend towards distributed generation, the problem of power quality is taking new dimensions. The quality of the electrical power is affected by many factors like harmonic contamination, due to non-linear loads, such as large converters, rectifiers, voltage and current flickering due to arc in arc furnaces, sag and swell due to the switching of the loads etc. The concept of custom power was introduced to distribution systems for improving the system performance. The aim thus, during this work, is to spot the prominent concerns within the area and thereby to suggest measures which will enhance the quality of the power, keeping in mind their economic viability and technical consequences.

The power transmitted over an ac transmission line is a function of the line resistance, the magnitude of sending-end and receiving-end voltages, and also the phase angle between these voltages. Traditional techniques of reactive line compensation and step-like voltage adjustment are typically used to alter these parameters to attain power transmission control. Fixed and mechanically switched series and shunt reactive compensators were used to modify the natural characteristics of the transmission lines so as to achieve the required effective impedance between the sending and receiving-ends to fulfil power transmission necessities. Voltage regulating and phase shifting transformers with mechanical tap-changing gears are used to minimize the voltage variation and power flow management. These typical methodology give adequate management under steady-state and slowly changing system conditions, however are mostly ineffective in handling dynamic disturbances.

II. LITERATURE REVIEW

The UPFC, which was proposed by L. Gyugyi in 1991 [1], [3], [4], is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for a flexible, reliable and economic operation and loading of power system. Several references in technical literature can be found on development of UPFC steady state, dynamic and linearized models. Steady state model referred as an injection model is described in [5]. UPFC is modelled as a series reactance together with the dependent loads injected at each end of the series reactance. If a UPFC is operated in the automatic control mode (i.e. to maintain a pre-specified power flow between two power system buses, the sending and the receiving buses, and to regulate the sending end voltage at the specific value) the UPFC sending end is transformed into a PV bus while the receiving end is transformed into a PQ bus, and conventional load flow (LF) program can be performed [6]. This method is simple and easy to implement but it will only work if real and reactive power flows and the sending bus voltage magnitude are controlled simultaneously. It should be also mentioned that there is no need for an iterative procedure used in [6] to compute UPFC control parameters. They can be computed directly after the conventional LF solution is found. Due to the advantages that the automatic power flow control mode offers, this mode will be used as the basic operation mode for the most of the practical applications. Therefore, this model will be discussed in the fourth chapter of this thesis. Series and shunt transformer losses are taken into account. A Newton-Rhapson based algorithm for large power systems with embedded FACTS devices is derived in [7].

In [8] the algorithm was extended to include UPFC application. It allows simultaneous or independent control of real and reactive powers and voltage magnitude. The algorithm itself is very complicated and hard to implement. It considerably increases the order of the Jacobin matrix in the iterative procedure and is quite sensitive to initial condition settings. Improper selection of initial condition can cause the solution to oscillate or diverge.J. Guo et.al. given a novel control approach for a unified power flow controller for power grid oscillation damping. This control is easy to implement, nevertheless is valid over a wide range of operative conditions. It is also effective within the presence of multiple mode of oscillation. The current management is enforced in many check systems and is compared against a traditional PI control [1]. Jungsoo Park presented the modelling of VSI type system controllers and control method for power system dynamic stability studies. They considered the Static Compensator, the Static Synchronous Series Compensator and also the Unified Power Flow Controller. In this paper, these FACTS controllers are derived within the current injection model. The result is verified by the nonlinear analysis victimization the time-domain simulation [2]. Kwang M. Son, et.al. given a Newton-type current injection model of the unified power flow controller (UPFC) for finding out the impact of the UPFC on the low-frequency oscillations. Since the proposed model is a Newton-type one, it is conceptually simple and gives quick convergence characteristics. The model is applied to an inter-area power oscillation damping regulator design of a simple two-area power grid.

III. BLOCK DIAGRAM OF UPFC

The UPFC consists of two three phase inverters connected in cascade in such a way that inverter I is connected in series with the provision voltage through a transformer inverter II is connected in parallel with the load. The main purpose of the shunt compensator is to catch up on the reactive power demanded by the load, to eliminate the harmonics and to control the common dc link voltage. The series compensator is operated in PWM voltage controlled mode which injects quadrature voltage such that the receiving end voltage is usually maintained at the desired value. The two inverters operate in a very coordinated manner. The UPFC will at the same time control the active and reactive power flow and voltage magnitude. But it has very little impact on voltage angle.The real, reactive power, and voltage balance of the unified power-flow control (UPFC) system is analysed. Two vital results associated with UPFC control are shown during this paper. First, the shunt converter provides all of the specified reactive power throughout the power-flow changes if the UPFC bus voltage is constant. This voltage can be controlled from the sending side as well as from the receiving side. The fundamental management strategy is specified the shunt converter controls the transmission-line reactive power flow and therefore the dc-link voltage.

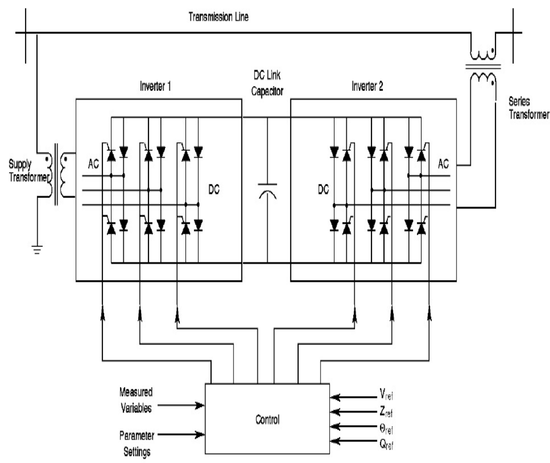

Fig. 1 Block Diagram of UPFC

The series converter controls the transmission line real power flow and therefore the UPFC bus voltage. The real/reactive power coordination controllers within the UPFC system can acquire smart performance each during transient and stable conditions. Inclusion of the real power coordination controller in the UPFC system avoids excessive dc-link voltage excursions and improves its recovery throughout transient conditions. Experiments have been conducted to verify the effectiveness of the proposed control strategy. The structure of UPFC contains back to back connected AC to DC voltage source converters operated from a common DC-link capacitor. 1stconvertor is connected in shunt and therefore the second one in series with the line. The shunt converter is primarily accustomed provide active power demand of the series converter through a common DC link. Shunt Converter can also generate or absorb reactive power, if it is desired, and thereby give independent shunt reactive compensation for the line. Series Converter gives the main function of UPFC by injecting a voltage in series with the line via ac voltage source with controllable magnitude and phase angle.

The voltage sources Vsh and Vse are obtained by converting DC voltage to AC voltage. The conversion from DC voltage to AC voltage is obtained by using standard bridge circuits. These bridge circuits use GTO as their building blocks. Since these circuits convert DC voltage to AC voltage, they are termed as voltage source converters (VSC). The control system associated with VSC allows it to adjust its magnitude and phase angle. The term "inverter" has also been used to denote the VSC.Consider now the connection of two VSC connected back to back with a common DC Link capacitor 'C' as shown in Fig. 1. Such an arrangement allows for al1 the three functions namely series, shunt and phase angle compensation to be unified in one unit. Inverter 1 is connected to a shunt transformer and the inverter 2 is connected to a series transformer.It is readily seen that the VSC connected to the shunt transformer can perform the function of a variable reactive power source similar to that of shunt compensator. In addition, the inverter 1 can charge the DC link capacitor. Inverter 2 can provide series or phase angle compensation by injecting a series voltage of proper phase relationship. In the case of series compensation, inverter 2 can function independent of the inventer 1, as inverter 2 supplies/consumes only reactive power and does not have any real power exchange with inventer 1. In such a case, the DC link capacitor voltage will ideally be constant. In the case of phase angle compensation, the series voltage source Vse has an arbitrary phase relationship with the transmission line current Ise and does have real and reactive power exchange with the transmission line. Under this mode of operation, the real power generated or consumed by inverter 2 (Pse) will lead to the discharging or charging of the DC link capacitor respectively. In the case of red power generation by inverter 2 (Pse), the DC link capacitor discharges, and the decrease in the voltage will reflect as a load on inverter 1. Under this circumstance, inverter 1 will provide the necessary real power (Psh) and charge up the DC link capacitor. In the case when the inverter 2 consumes real power (Pse,) leading to charging of the DC link capacitor and subsequent increase in its voltage, inverter 1 will supply the excess real power (Psh) back to the line through the shunt transformer. In essence, the UPFC provides an alternate path for the real power i.e. from the bus to which the shunt transformer is connected, through inverter 1 to the capacitor, through inverter 2 and to the transmission line through the series transformer. Inverter 1 and inverter 2 can generate reactive power independently. In summary, the above arrangement of two VSC connected back to back coupled by a DC link capacitor can perform the job of all the three types of compensation.

IV. D-Q THEORY STRATEGY

In this strategy, the D-Q axis current in the transmission line is individually controlled allowing for independent control of real and reactive power flow. The D-Q axis could be with respect to UPFC bus voltage or the remote end bus voltage. In this strategy, the series injected voltage is split into two components. One is in-phase with the D-axis arid the other in-phase with the Q-axis. Similarly, the transmission line current is split into D and Q axis currents. The D-axis voltage controls the transmission Line real power by varying the D-axis current in the transmission line and the Q-axis voltage controls the transmission line reactive power by varying the Q-axis current in the transmission Iine. Thus the in-phase series injected voltage component (D-axis) that controls the transmission line real power flow varies the line side voltage and the Q-axis component of the series injected voltage that controls the reactive power varies the phase angle of the UPFC bus. To achieve this type of strategy, the control system employs cascaded linear controllers. Proportional-Integral (PI) controllers have been used to implement the D-Q axis control strategy for the series inverter. The coordination between the series and the shunt inverter control system has been considered. The problem with this strategy for the series inverter is the complexity of the control system. Two control loops are required to regulate the real and reactive power flow. The outer loop is to set the reference for the inner loop. The inner loop tracks the reference thus providing the control inputs to the series inverter. Further the problem of deterioration of the control system performance at operating points other than the one at which it is designed is a point to be considered. The shunt inverter control system is also based on the D-Q axis strategy and controls the shunt reactive power and the shunt inverter real power. The control of DC link capacitor voltage which is very essential for the proper operation of the UPFC is done by another control loop that adjusts the shunt inverter real power reference. This further complicates the control system. Further, they have neglected the dynamics of the DC link capacitor while designing their control system. By doing so, the control system design may not provide the best PI control gains. A control system based on D-Q axis theory has been published in the literature by Rourid et. al. The strategy that has been used is that the D-axis voltage component controls the transmission line reactive power and the Q-axis voltage component of the series injected voltage controls the transmission line real power. This is in contrast with the strategy used by Papic et.al.where the transmission line real power flow was controlled by the D-axis voltage and the transmission line reactive power flow was controlled by the Q-axis voltage. In this case, the WFC is assumed to be located at the receiving end. Based on the receiving end real, reactive powers and receiving end D-Q axis voltages, current references of the series inverter are generated. Two PI controllers are used to generate the required D-Q axis control voltages for the series inverter to obtain desired real and reactive power flow in the transmission line. For the shunt inverter, based on the sending end real power, reactive power references and sending end D-Q axis voltages, the sending end D-Q axis current references are then generated. Knowledge of the sending and receiving end current references are used to generate the current references for the shunt inverter. By doing so, the shunt reactive power and the DC link capacitor voltage are controlled. Remote end signal measurement is required for this type of control system to operate. This would necessitate remote sensing units to be installed at the sending end. Further, coordination between the series and the shunt inverter control system has not been considered by the authors.

V. MODELLING OF UPFC

The shunt converter of the UPFC controls the reactive power flow in the transmission line and dc-link voltage. The control diagram for the shunt part of the UPFC is shown in Fig 2. The control scheme consists of two loops the outer loop and the inner loop. The outer current loop generates the reference current with coordination control and the inner current loop makes the shunt device output the required currents. The axis current is controlled to manage the dc-link voltage and balance the real power of the UPFC. The axis current is controlled to manage the transmission-line reactive power flow. The decoupled system has been used to attain simultaneous control of the shunt converter input current.

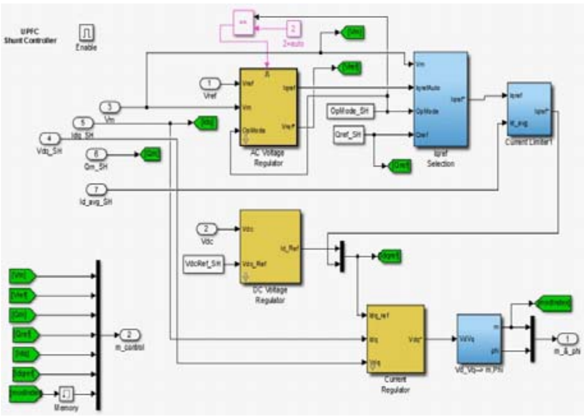

Fig. 2 MATLAB Simulink of Shunt Converter

Coordination control schemes are applied in each transmission-line reactive power flow and dc-link voltage control to get higher dynamic performance. Within the axis coordination control scheme, the transmission-line reactive power-flow variation reference is added to the reactive power-flow PI regulator output with a gain $2/3V_{1d}$. So the shunt device will generate an acceptable quantity of reactive power to compensate the reactive power-flow modification with a fast response. Further, the inner control system loops are quick-acting PI controllers and guarantee fast supply of each the series converter real power demand and also the reactive power required for reactive power-flow control by the shunt converter.The series converter provides simultaneous control of the bus voltage and real power flow in the transmission line. To do so, the series converter injects the sinusoidal voltage with variable amplitude that is equivalent to series connected inductive or capacitive reactance with the transmission line.

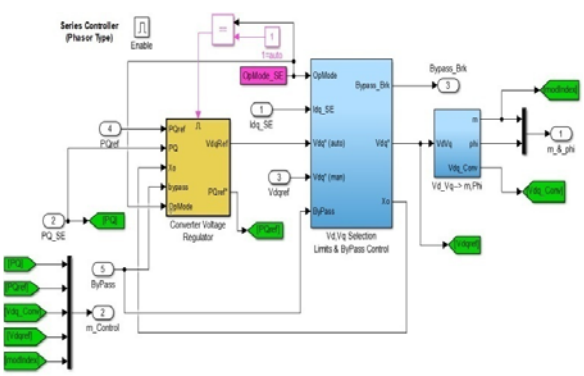

Fig. 3 MATLAB Simulink of Series Converter

The heart of series converter is a voltage source inverter (VSI) that's supplied by a DC storage capacitor. The series converter injected voltage is decomposed into two components. The transformation is the same as that used in shunt converter control. The fundamental part is in quadrature with the line current and emulates an inductive or capacitive reactance in series with the transmission line, and a small part of the injected voltage is in phase with the line current to cover the losses of the inverter. If the inserted voltage is leading the line current, the series converter behaves like a capacitive reactance connected in series with the line, producing the line current as well as power flow through the line to increase. If the injected voltage is lagging the line current, it will emulate an inductive reactance in series with the line, generating the line current as well as power flow through the line to reduce.

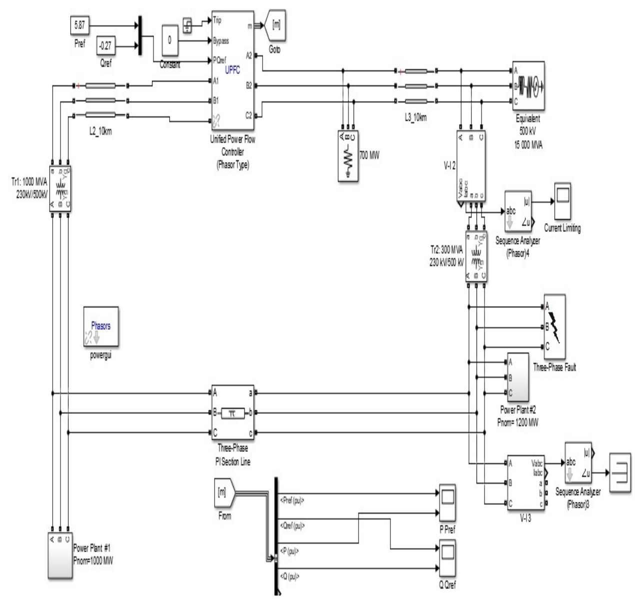

Fig. 4 MATLAB Simulink of UPFC

VI. RESULTS

An experimental UPFC system has been built to test the power control in transmission line. Recent advances in high-voltage IGBT technology allow for higher switching frequency with lower loss, and this allows for practical implementation of PWM control for high-power converters. So in the experiment, both the shunt converter and the series converter have been built as a three-phase PWM converter with IGBT as the power device. The UPFC device is inserted into a transmission line, and with the help of the UPFC, the power flow in the transmission line can be controlled effectively while maintaining the UPFC bus voltage constant. The parameters of the whole systems are given below:-

Sending end voltage Vs - 380V (line-line)	Receiving end voltage Vr - 380V (line-line)
The transmission angle r - 30 degree	Shunt transformer turns ratio Tsh - 2.5:1 (Y-D)
Series transformer turns ratio Tse - 6:8 (Y-D)	Sending end line inductance LS - 18mH
Transmission line inductance L - 60mH	Shunt converter output filtering inductance Lsh - 6mH
Series converter output filtering inductance Lse - 1mH	Series converter output filtering capacitance Cse - 10Mf
DC-link capacitor Cdc - 9400µF	DC-link voltage Vdc - 400V

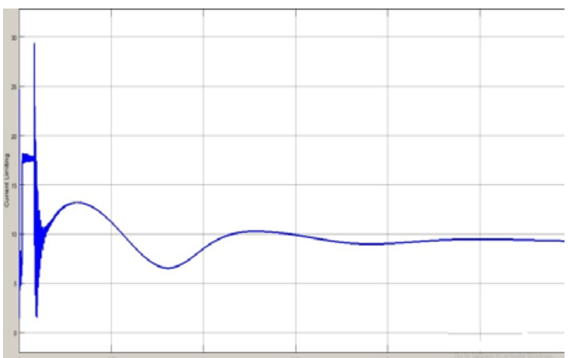

Fig.5 current limiting

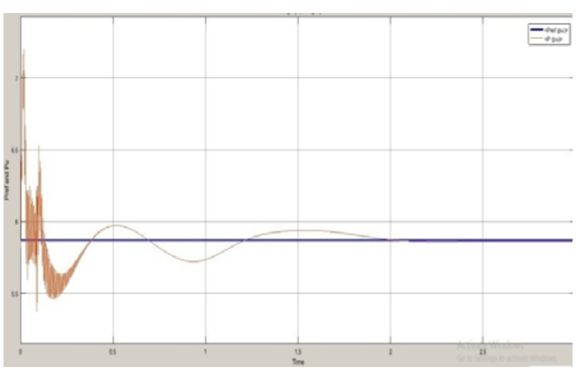

Fig. 6 P(ref) Vs P(actual)

The UPFC under study is connected to the transmission line system. In order to simulate the operation, the UPFC power control system model has been developed and simulated in Matlab/Simulink. The components of the simulation model are built with standard electrical component blocks from the SimPower Systems block in Matlab/Simulink library. Power control in transmission line: - With and without compensation.

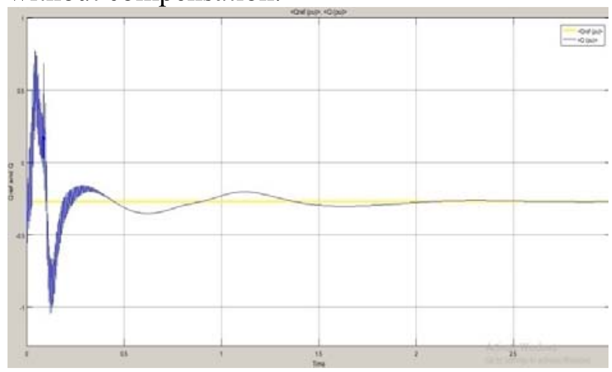

Fig. 7 Q(ref) Vs Q(actual)

The operation of UPFC is studied by applying three phase solid fault on the transmission line. The fault occurs at time 0.1 to 0.2 sec for duration of 0.1 sec. As shown in Fig. 5, when fault occurs, the current of the AC supply line increases and returns to normal after the fault is removed. A slight transient is noticed after the removal of fault. The Fig.6 and 7 shows that during the duration of fault, the real power is absorbed by the UPFC and the reactive power is generated by the UPFC.

VI. CONCLUSION

The Real, reactive power and voltage balance of the UPFC system are analysed. The basic control strategy is such that the shunt converter of the UPFC controls the transmission-line reactive power and the dc-link voltage. The series converter controls the transmission- line real power flow and the UPFC bus voltage. The shunt converter provides all of the required reactive power during the power flow changes if the UPFC bus voltage is constant. The UPFC bus voltage can be controlled both from the sending side and from the receiving-end side.

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