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A Novel Method for Hysteresis based Control of UPFC

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Abstract— **Appropriate design and use of Unified Power Flow Controller (UPFC), which has the ability of controlling the bus voltage level and transmission line power flow simultaneously, provides suitable conditions to improve restructured power systems operation. In this paper, a novel control method is proposed for Hysteresis based UPFC, which uses four degrees of freedom to control bus voltage, DC link voltage, and active and reactive transmission line power flows independently. Results obtained by simulations with PSCAD/EMTDC show that proposed control method is more effective than the reported methods in achieving better power quality indices and more stability i.e. less overshoots and settling times.**

***Index Terms*-- UPFC, Hysteresis band switching, FACTS, PSCAD/EMTDC.**

I. INTRODUCTION

IN addition to bus voltage control as one of the critical issues which should be taken into account in power networks management, control of active and reactive power flows is one of the most important requirements of operation and management of power transmission systems. Accordingly, the possibility of controlling power flow in an electric power system without generation rescheduling or topology changes and improving restructured power systems operation can be achieved using the Flexible AC Transmission systems (FACTS) technology. In particular, UPFC (as a combination of static synchronous series compensator (SSSC) and a static VAR compensator (STATCOM) could be considered as a comprehensive active and reactive power compensator capable of independently controlling both the active and reactive power flow in the line. Moreover it is able to control the bus voltage, simultaneously.

Furthermore, on the power electronics hardware aspect, switching method is an important issue that should be noted. Three major switching methods have been reported to use in UPFC: Multi-pulse, PWM and Hysteresis switching [2].

In addition, different control methods with various control objectives have been presented in the papers. These control objectives are bus voltage, DC link voltage, and active and reactive power flows.

Reference [2] proposed a PWM-based control method for UPFC which makes active and reactive power follow the reference values by controlling the amplitude and phase of series inverter current, and regulates bus voltage and DC link voltage by controlling the amplitude and phase of shunt inverter current. It also uses PI controller while in [5] Genetic Algorithm is used to find the best solution for controller parameters. Reference [6] also proposed a similar control method using fuzzy logic controllers.

As expressed in [7], there exist four degrees of freedom to control UPFC which are amplitudes and phase angles of both series and shunt branches of UPFC. All these four degrees of freedom have not been considered in the papers which use Hysteresis band as switching method in UPFC. For instance, in [3] only bus voltage is regulated by controlling the phase angle of transmission line current and there is no control on DC link voltage and transmission power flows; hence, this reference employed only series branch current phase angle as degree of freedom. Also, [8] has used amplitude of shunt branch current to regulate bus voltage and phase of series branch current to improve transient stability, as two degrees of freedom. In addition, some other papers investigated the effects of UPFC on stability [9, 10], network security [11], transmission line capacity enhancement [12, 13], and sub-synchronous resonance [14] but none of them employed all four available degrees of freedom. Paper [15] discusses a sample case and its transmission limits which can be exceeded by using the method proposed in this paper.

In this paper, a straight forward control method for series branch of UPFC is proposed and all four degrees of freedom are employed to regulate bus voltage, DC link voltage, and active and reactive power flows of transmission line. In detail, these degrees of freedom are amplitudes and phase angles of currents of both series and shunt branches.

II. HYSTERESIS CONTROLLED SWITCHING METHOD

Fig. 1 illustrates the connection of UPFC, which its power circuit is shown in Fig. 2, to the power system. The shunt and series branch terminals are depicted in both Fig. 1 and Fig. 2.

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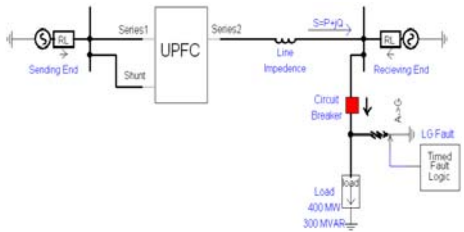

Figure 1. Connection of UPFC to the power network.

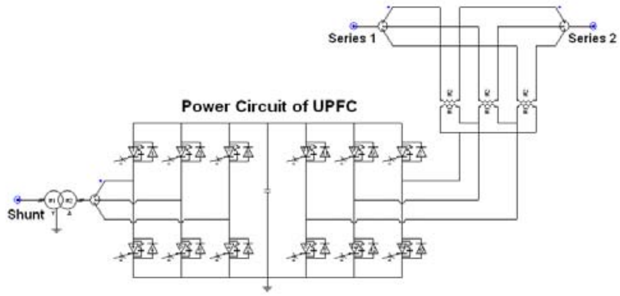

Figure 2. Power circuit of UPFC.

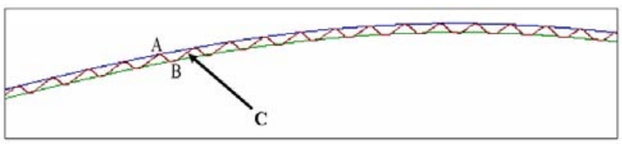

Figure 3. A part of Hysteresis-switched current waveform; A) Upper boundary of Hysteresis band; B) Lower boundary of Hysteresis band; C) Current waveform.

Hysteresis band switching method is based on turning on or off the power switches such that the actual current waveform (Fig. 3C) is maintained in a so-called Hysteresis band, which is determined between two boundaries (Fig. 3A, 3B) up and down of the predetermined reference waveform (Fig. 3). This method has the advantage of reduction of low order harmonics over multi-pulse method. Also, the main harmonic contents are of high orders which could be easily eliminated by filtering. Thus this method will decrease the bad effects of low order harmonics, [3] and [4].

Generally the proposed control method has two parts. In the first part the amplitude and phase of the HV side current of transformer, connecting the shunt converter to transmission line, is used to regulate bus voltage and DC link voltage on reference values. The second part uses the amplitude and phase of line current to control active and reactive power flows. However in some papers series branch current is used to regulate bus voltage [3].

III. Problem Statement

A. Not using all four degrees of freedom available for Hysteresis-based UPFC control

Although there are four degrees of freedom in UPFC, not all of them are used in papers which proposed Hysteresis based control methods for UPFC. Moreover there is no control on line power flow in these methods. As a case in point, the UPFC proposed in [8] has neither control on the phase angle of shunt branch current nor on the amplitude of series branch current. In detail, the control system uses the amplitude of shunt branch current to regulate bus voltage and the phase of injected current is dictated by phase angle of bus voltage. Besides, series branch control system uses only the phase angle of series branch current in order to synchronize the rotational velocity of generator axis. Thus, the paper mentioned uses two degrees of freedom to regulate bus voltage and to enhance transient stability of the power network, while other two degrees of freedom are excluded. The control system presented in [3] which employs one degree of freedom controls the bus voltage by adjusting the phase angle of series branch current and has no control on other power system parameters.

B. Power fluctuations due to malfunction of shunt branch control system

If the control system of shunt branch of UPFC does not work properly, the control system of series branch is not able to perform its function well and introduce power fluctuationsto the system. Accordingly, the active and reactive power fluctuations occurred would cause adverse impacts on insulation and voltage stability. However, in the papers, the series branch control system is designed assuming that the other control system is completely reliable.

IV. Novel Method

A. Employing all four degrees of freedom to control UPFC

In this paper, the amplitude and phase angle of current of series and shunt branches are employed as four degrees of freedom. The control system of shunt branch is based on the model presented in [2] and the series branch control system introduced in the next step is designed in a straight-forward procedure to control active and reactive power flows of transmission line.

B. Series branch control system

a) Control system of series branch

The novel method applied to series branch in this paper, employs the amplitude and phase angle of series branch current as two degrees of freedom. In fact, the aim of the control system is to adjust active and reactive power flows on their predetermined reference values, P_{ref} and Q_{ref}. Obviously, it would be possible to control two system parameters independently, if two orthogonal quantities are used as control parameters of control system. Therefore, two control parameter $S=\sqrt{P^2+Q^2}$ and $\dfrac{Q}{P}$ which indicate the amplitude and phase angle of transmission line apparent power are considered in the proposed method.

In a transmission line, apparent power is defined as below:

$$S = V.I^* = (|V|\angle\delta_V).(|I|\angle\delta_I)^* = |V|.|I|\angle(\delta_V-\delta_I) \quad (1)$$

If we assume that the phase angle and rms value of bus voltage is zero and 1pu, respectively,

$$S = P + jQ = |I|\angle-\delta_I \Rightarrow \begin{cases} |I| = |S| = \sqrt{P^2+Q^2} \\ \delta_I = -Arc\tan\dfrac{Q}{P} \end{cases} \quad (2)$$

then,

$$S_{ref} = P_{ref} + jQ_{ref} \Rightarrow \begin{cases} |S_{ref}| = |I_{ref}| = \sqrt{P_{ref}^{\ 2} + Q_{ref}^{\ 2}} \\ \delta_{I_{ref}} = -Arc\ \tan \dfrac{Q_{ref}}{P_{ref}} \end{cases} \quad (3)$$

If the active and reactive power flows are adjusted on their reference value, we have:

$$\left.\begin{matrix} P = P_{ref} \\ Q = Q_{ref} \end{matrix}\right\} \Rightarrow S = S_{ref} \Rightarrow \begin{cases} |I| = |I_{ref}| \\ \delta = \delta_{ref} \end{cases} \quad (4)$$

$$\begin{cases} |I| = |I_{ref}| \Rightarrow |S| = |S_{ref}| \\ \Rightarrow \sqrt{P^2 + Q^2} = \sqrt{P_{ref}^{\ 2} + Q_{ref}^{\ 2}} \end{cases} \quad (5)$$

And also,

$$\begin{cases} \delta_I = \delta_{I_{ref}} \Rightarrow Arc\ \tan \dfrac{Q}{P} = Arc\ \tan \dfrac{Q_{ref}}{P_{ref}} \\ \Rightarrow \dfrac{Q}{P} = \dfrac{Q_{ref}}{P_{ref}} \Rightarrow Q.P_{ref} - P.Q_{ref} = 0 \end{cases} \quad (6)$$

According to the equations above, the apparent power is related to the amplitude of current with a constant factor which is computed below:

$$|S| = \sqrt{3}|V_{rms}||I_{rms}| = \frac{\sqrt{3}}{\sqrt{2}}|V_{rms}| * I_{\max} \Rightarrow I_{\max} = \frac{\sqrt{2}}{\sqrt{3}|V_{rms}|} * |S| \quad (7)$$

$$\Rightarrow k = \frac{I_{\max}}{|S|} = \frac{\sqrt{2}}{\sqrt{3}|V_{rms}|} \quad (8)$$

Based on the equations above, it is sufficient to adjust $\sqrt{P^2 + Q^2}$ and $Q.P_{ref} - P.Q_{ref}$ on their reference values $\sqrt{P_{ref}^{\ 2} + Q_{ref}^{\ 2}}$ and zero respectively to control active and reactive power flows appropriately. Hence, the amplitude and phase angle of transmission line current is chosen in the proposed method.

Due to the fact that the values S_{ref} and k are known constant, the reference value of amplitude of current will be known, if the bus voltage is regulated on 1pu. Thus, it is required to add an auxiliary control system to series branch to regulate bus voltage on 1pu.

b) *Auxiliary control system of series branch*

To prevent power flow fluctuations due to malfunction of shunt branch control system, an enabler is designed as auxiliary control system. This enabler lets series control system be active if the active and reactive power flows are around their reference points e.g. +-5%. In fact, the enabler activates series branch control after the parameters which are to be controlled by shunt branch are in an acceptable range of values. In the other words, the enabler system places a higher priority on the control system of shunt branch than that of series branch, so if the bus voltage and DC link voltage are not in an acceptable range then the series branch control system will not be activated.

V. SIMULATION RESULTS

The UPFC control systems introduced in [5] and [8] were simulated in addition to new proposed method to compare the effectiveness, using PSCAD/EMTDC. To simplify addressing the methods, till end of this section, methods in [5], [8] and new proposed one will be named old1, old2 and new control method, respectively. The novel control method is simulated in two case studies and the results are compared with the other methods in order to show the effectiveness of the control method proposed in this paper.

A. *Case Study 1*

The control system used in [5] which employs PWM switching method controls transmission active and reactive power flows using amplitude and phase of series branch current and regulates bus voltage and DC link voltage using amplitude and phase of shunt branch current. A UPFC module was built on basis of control method used in [5]. This module and that of novel method presented in this paper, were used in power system of Fig. 2 in which reference bus voltage is 1pu (400KV) and active and reactive power references are -485 MW and 45 MVAR, respectively. Thus the operation conditions of two power systems are similar.

To evaluate the response speed of two control methods, a single phase fault on phase A of power system showed in Fig. 2 was considered. This fault occurs in t = 1.7 s and is cleared 0.1 s later.

Fig. 4 and Fig. 5 display simulated waveforms of controlled parameters of power system in new method and method old1. Fig. 4-A and Fig. 5-A show that voltage levels in both methods has less than 0.5% tolerance. In the new method DC voltage has maximum fluctuation of 2.5% while the old1 method has maximum fluctuation of 5% which is displayed in Fig. 4-B and Fig. 5-B. In the fault duration, active power fluctuation of old1 method is about 75 MW (15%) but the new method has only 2.5 MW (0.5%), as shown in Fig. 4-C and Fig. 5-C. Fig. 4-D and Fig. 5-D display that reactive power maximum fluctuation is about 3 MVAR (6.6%) which is less than that of old1 method which is about 125 MVAR (300%).

Moreover Fig. 4 shows that bus voltage and DC voltage are regulated on their reference values in less than 0.1 s, after the fault is cleared. Active and reactive powers are also regulated on their reference values in less than 0.15 s which is much better than that of old1 method's regulation time that is 0.3 s.

B. *Case Study 2*

In this section, the case studied in [8] is selected to make a comparison between the new and the old2 control methods of UPFC. So, the novel UPFC module is applied to the network

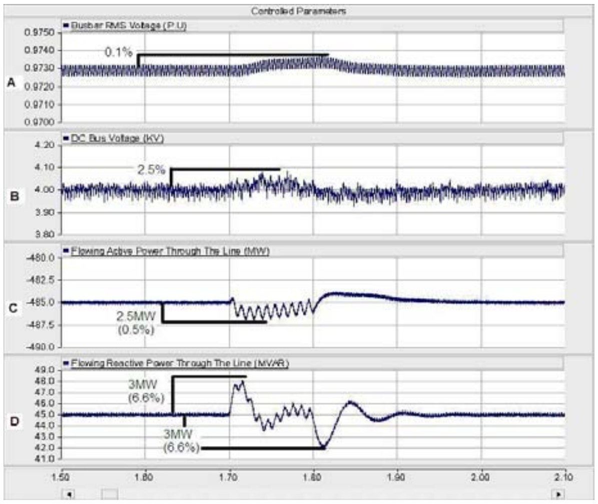

Figure. 4: Simulation Results of New method at Fault Duration Time for Case Study 1: A) Sending End Bus Voltage (pu) B) DC Link Voltage (KV) C) Transmission Line Active Power (MW) D) Transmission Line Reactive Power (MVAR)

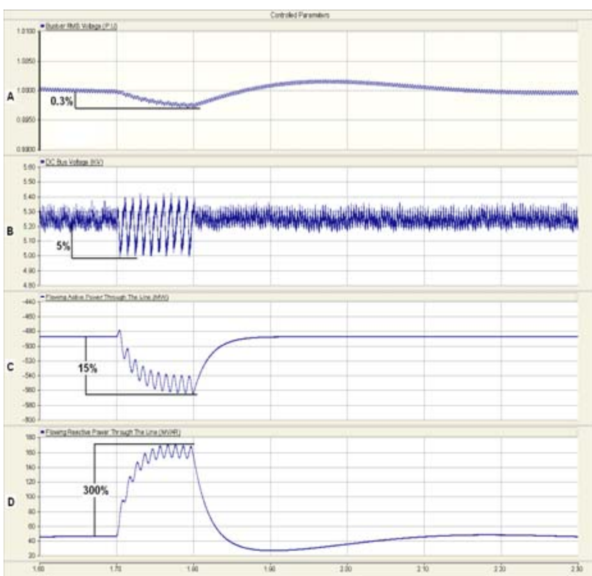

Figure. 5: Simulation Results of old 1 method at Fault Duration Time for Case Study 1: A) Sending End Bus Voltage (pu) B) DC Link Voltage (KV) C) Transmission Line Active Power (MW) D) Transmission Line Reactive Power (MVAR)

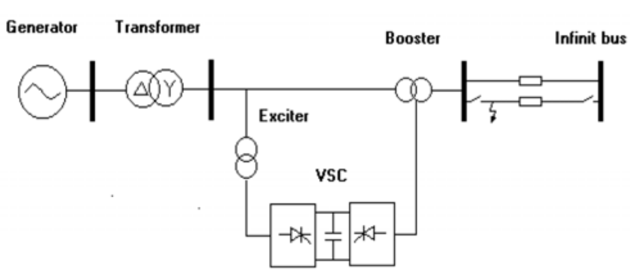

Figure. 6: The network studied for investigation of the novel UPFC impacts on power system transient stability and comparison with old2 control method

simulated in [8] instead of the old1 UPFC module. The other parameters of the power network studied in this section, illustrated in Fig. 6, are exactly same with the parameters assumed in [8].

Moreover, the reference values of system voltage and active and reactive power flows, in this paper, are assumed equal to the values offered in [8]. The reference voltage level and active and reactive power flows are equal 230kV, 200MW, and zero MVAR, respectively.

In order to analyze UPFC impacts on the transient stability of the power system, it is assumed that a three-phase fault is occurred on one of the transmission lines connected to the infinite bus at t=2sec as depicted in Fig. 6. Then, the circuit breakers of both sides of the line isolate the fault after 0.1 seconds. Finally, the circuit breakers close at t=2.3sec and the power system restores to its normal initial conditions.

For the first step, both UPFC modules, with novel control method and with old2 control method, were applied to the power network depicted in Fig. 6 and the system was simulated. The simulation results of the new method are shown in Fig. 7 and those of the old2 method are illustrated in Fig. 8.

Regarding the results shown in Fig. 7, the bus voltage is regulated between 0.9pu and 1.1pu, during the fault occurrence; so, the shunt branch control system has a proper effect on voltage regulation (Fig. 7-A). In addition, DC link voltage increases 225% using the new control method (Fig. 7-B) due to fault occurrence, where the results obtained in [8] show that DC link changes from 20kV to 70kV, 250% over reference voltage, if the old2 control method is used (Fig. 8-A). Besides, the results depict a maximum variation of 160MW or 80% in active power flow and a maximum variation of 160MVAR in reactive power flow in case of using the new control method (Fig. 7-C, 7-D), while the results of the old2 method simulation shows that the parameters mentioned are 40MW (20%) and 40MVAR, respectively (Fig. 8-B, 8-C). Despite this weakness of the new control method in comparison with the old2 method, the results illustrate that the settling time of the new control system is much less than that of the old2 method. In detail, the power flow fluctuations are completely damped 0.6 seconds after fault occurrence i.e. 0.3 seconds after power system restoration in new method (Fig. 7-C, 7-D), while the fluctuations are not settled until 2 seconds after the fault occurred in old2 method (Fig. 8-B, 8-C). Also, the current waveforms of shunt and series branches, which are illustrated in Fig. 7-E and 7-F, respectively, lets reader to track the reactions of the new control method from fault occurrence to complete damped condition.

According to the simulation results, the new control method represented in this paper has an appropriate impact on transient stability enhancement during fault occurrence, in addition to bus voltage and DC link voltage regulation and active and reactive power flow control. In the other words, reduction in the settling time of power flow fluctuations which is one of the most significant advantages of UPFC, improves power system transient stability.

VI. CONCLUSION

In this paper, Hysteresis band switching method is employed and four degrees of freedom available for UPFC is used in the control system, which has not been presented before, for

Hysteresis-based UPFC. In addition, a novel straight-forward control method is presented for series branch control system. This system controls active and reactive power flows of transmission line on their reference values by adjusting the amplitude and phase angle of series branch current. The simulation results and their comparison with the results obtained in other papers, prove that not only the control system proposed perform its main functions appropriately, but also it has a proper impact on power system stability.

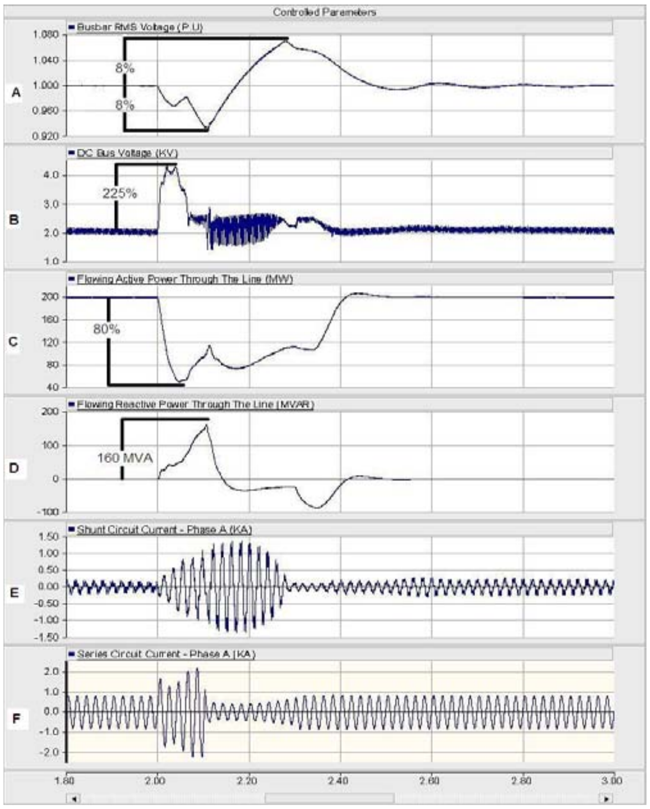

Figure. 6: Simulation result of the novel control method in case study 2. A) Bus Voltage (kV). B) DC link voltage (kV). C) Transmission line active power (MW). D) Transmission line reactive power (MVAR). E) Shunted branch current waveform (kA). F) Series branch current waveform (kA)

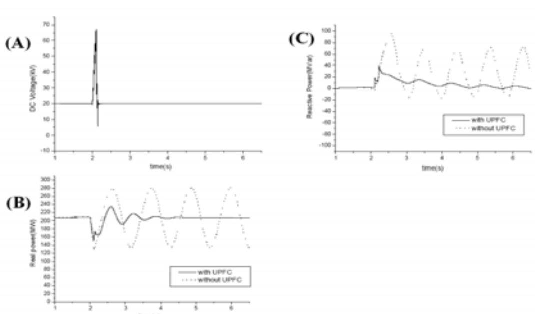

Figure. 8: Simulation result of the old2 control method in case study 2, obtained from [8]. A) DC link voltage (kV). B) Transmission line active power (MW). C) Transmission line reactive power (MVAR).

VII. References

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VIII. Biographies

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