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The Simulation Study and Dynamic Analysis of Unified Power Flow Controller for Industrial and Educational Purposes

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Introduction

In AC power systems, for many years to overcome the reactive power problems mechanical switched groups of capacitors and reactors are used. However, to control the switching of power capacitor and reactors has been a major challenge for engineers. Because during transient events such elements cannot provide the necessary compensation because of their slow response times and can really degraded the stability of the system after disturbance influences [2]. In power systems it was observed that compensation with the case of the semiconductor switches, the voltage crashes could be prevented and the transient and dynamic stability could be improved [3].

FACTS controllers are fast against traditional equipment because of their power electronic based structure and they increase the stability operating limits of the transmission systems when their controllers are properly tuned [4].

UPFC is the most versatile device among FACTS devices. It provides the control of transmission system parameters such as voltage, phase angle and line impedance in power systems [1–10]. There have been many studies intended for mathematical modeling, impacts on power systems and control system design for UPFC. In [11] authors have been developed mathematical models for steady state, transient stability and eigenvalue studies. In [12] CSI (current Source inverter) topology is used and applied to STATCOM in a power system. In [13], a STATCOM system is applied for compensation of displacement power factor under distorted mains voltage conditions. According to simulation results STATCOM is ensuring the displacement power factor compensation with good transient and steady state performance. Impacts of UPFC, STATCOM and SSSC on voltage stability have been investigated in [14]. It has been shown that these devices are regulate the voltage profile and increased the loadability margin of power systems.

Nowadays, control of power systems has a great importance. Especially requirement of energy increases constantly. Maximizing of the usage of available power systems with FACTS and suchlike hardwares is quite an agenda topic because of the fact that construction of new energy power plants is costly. This study presents a simulation program which can be used for investigation of effects of UPFC and other converter based FACTS devices on power system. UPFC system in this program is composed of equations obtained in d-q frame of reference. In simulation studies, control of bus voltage and active power control with UPFC is performed by adding inductive and capacitive loads to the system.

UPFC basic structure and operating principle

The Unified Power Flow Controller (UPFC) which is proposed in [1] has the capabilities of real time control and dynamic compensation of ac transmission systems. As seen in Fig. 1 UPFC is a combination of STATCOM and SSSC which was operated from a common dc capacitor.

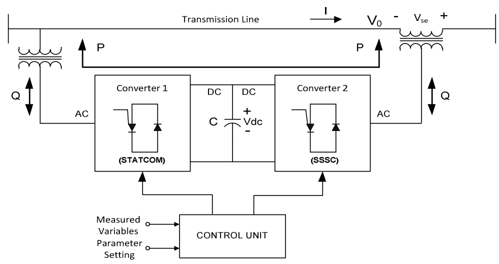

Fig. 1. Schematic diagram of UPFC

The configuration which is depicted in Fig.1 acts as an ideal ac to ac power converter. The real power can freely flow in either direction between the ac terminals of these two converters. Also each converter can exchange reactive power at its own ac terminal with the system [6].

UPFC system and mathematical modeling

Circuit scheme of the UPFC system has been depicted in Fig. 2. To simplify the dynamic analysis instantaneous three phase variables has converted to d-axis and q-axis components in a synchronously rotating d-q frame [15–17]. Quantities in equations are all in pu values. UPFC system is a two machine system. V_s and V_r are sinusoidal voltage sources which generates balanced three phase voltages. UPFC converters are represented by voltage sources V_{sh} and V_{se} respectively. Converters here are assumed that ideal controllable voltage sources. R_{sh} and X_{sh} are shunt converter's coupling transformer resistance and leakage reactance respectively. UPFC dc link equivalent is not take place in this circuit but presented in UPFC dynamic model.

In Fig. 2 energy transmission system named as transmission line 1 and transmission line 2. R_s and X_s are transmission line resistance and reactance respectively. Transmission line resistance and reactance also includes the series transformer leakage reactance and resistance.

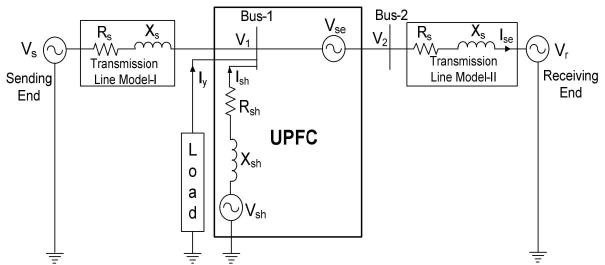

Fig. 2. UPFC System

UPFC and transmission system parameters are as follows; R_s=0.0075, X_s=0.075, X_{sh}=0.15, R_{sh} =0.01, b_{cap}=2.0, g_{cap} =0.02, V_s =1.0 $\angle 30^o$,V_r=1.0 [6]. System load is P±jQ=3±j2.25 pu. Quantities are all in pu. Base values of system are Sb=100 MVA, Vb=400 kV.

Dynamic model of UPFC

Mainly, UPFC has three control parameters; these are shunt reactive current, magnitude and angle of series voltage. Real and reactive power flow can be controlled independently by injecting a series voltage of the appropriate magnitude and angle [17]. Bus voltage can be controlled by using shunt reactive power injection. For this purpose shunt current is split into real and reactive current components. Real component of this current is in phase with bus 1 voltage. Reactive current is in quadrature with bus 1 voltage. According to d-q frame of reference, UPFC shunt converter current is given by eq. (1) and (2), [6]:

$$\frac{di_{dsh}}{dt} = -\frac{R_{sh}\omega_b i_{dsh}}{x_{sh}} + \omega i_{qsh} + \frac{\omega_b}{x_{sh}}\left(V_{dsh} - V_{1d}\right). \quad (1)$$

$$\frac{di_{qsh}}{dt} = -\frac{R_{sh}\omega_b i_{qsh}}{x_{sh}} - \omega i_{dsh} + \frac{\omega_b}{x_{sh}}\left(V_{qsh} - V_{1q}\right) \quad (2)$$

The d-q components of shunt current can be converted to its reactive and active components [6]:

$$\begin{cases} i_{rsh} = i_{dsh}\cos\theta - i_{qsh}\sin\theta, \\ i_{psh} = i_{dsh}\sin\theta + i_{qsh}\cos\theta, \end{cases} \quad (3)$$

where θ is expressed as $\theta = \tan^{-1}\frac{V_{1d}}{V_{1q}}$ [6].

For control of shunt current the scheme has been used in Fig. 3 [6]. In that scheme active and reactive currents can be converted into d-q components by using eq.(4). Outputs of that scheme are shunt branch voltages [6].

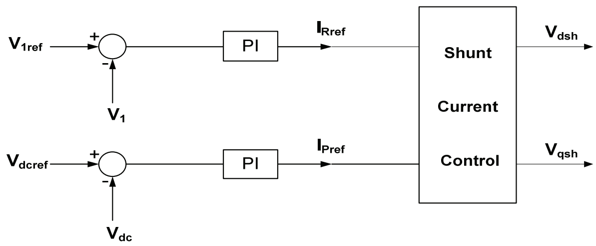

Fig. 3. Shunt branch control scheme

$$\begin{cases} i_{dsh} = i_{rsh}\cos\theta + i_{psh}\sin\theta, \\ i_{qsh} = -i_{rsh}\sin\theta + i_{psh}\cos\theta. \end{cases} \quad (4)$$

Performance of UPFC is related to stability of voltage of DC-link between series and shunt converters. To obtain a stable voltage an appropriate model of DC-link must be used [7]. Such an equivalent circuit of DC-link has shown in Fig. 4. In that equivalent circuit g_{cap} and b_{cap} is conductance and susceptance of capacitor respectively. This model is based on the principle of instantaneous power balance. Neglecting the losses active power supplied from shunt converter must be equal to the active power absorbed by the series inverter [6, 7, 18].

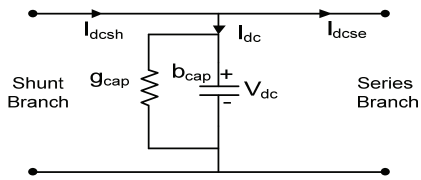

Fig. 4 UPFC DC-Link equivalent circuit

By using this model a dynamical equation of dc link voltage can be obtained as in eq. (5) [6, 7].

$$\frac{dV_{dc}}{dt} = -\frac{g_{cap}\omega_b V_{dc}}{b_{cap}} + \frac{\omega_b}{b_{cap}}\left(i_{dcsh} - i_{dcse}\right) \quad (5)$$

As is known V_{dc} voltage is function of control variables of shunt and series converters. The real power drawn or supplied by the series branch or by the shunt branch exposes as dc side currents I_{dcse} and I_{dcsh} respectively. Because of variable real series voltage injection, the capacitor voltage tends to change due to the losses. Thus in the scheme of shunt brunch, output of DC voltage adjusted as real current reference to compensate the losses by I_{dcsh} [6]. To realize real and reactive power flow control it is required to inject series voltage of the appropriate magnitude and angle. According to Fig. 2 receiving end d-q components are defined as in eq. (6) [6]:

$$\begin{cases} \dfrac{di_{dse}}{dt} = -\dfrac{R_s \omega_b i_{dse}}{x_s} + \omega i_{qse} + \dfrac{\omega_b}{x_s}\left(V_{2d} - V_{rd}\right), \\ \dfrac{di_{qse}}{dt} = -\dfrac{R_s \omega_b i_{qse}}{x_s} - \omega i_{dse} + \dfrac{\omega_b}{x_s}\left(V_{2q} - V_{rq}\right), \end{cases} \quad (6)$$

where $V_{2d} = V_{1d} + V_{dse}$ and $V_{2q} = V_{1d} + V_{qse}$. ($V_{2d}$, V_{2q}), (V_{1d}, V_{1q}), (V_{dse}, V_{qse}), and (V_{rd},V_{rq}) d-q components of bus 2, bus 1, series brunch and receiving end voltages respectively [6].

If it assumed that V_s=V_1=constant, power at receiving bus P_R is approximately equal to that at bus 2 P_2 of the UPFC in the steady state. Power at bus 2 is given in eq. (7) [6].

$$P_2 = V_{2d} i_{dse} + V_{2q} i_{qse}. \quad (7)$$

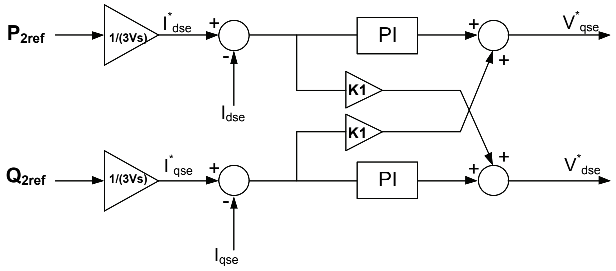

Fig. 5. Series branch control scheme

Main function of UPFC is the control of active and reactive power flow. In this study control scheme which is depicted in Fig.5 is based on the cross-coupling control method has been used for the control of series voltage injection similar to references [7-9].

As shown in Fig. 5 the d-q components of current references generated from the active and reactive power demands are compared with the transmission line measured values. Two PI controllers are used to produce the d-q components of voltage references, while gain K1 acts as a damping resistor. The d-q components of voltage references according to this scheme for the series converter is expressed as in eq. (8) [8].

$$\begin{bmatrix} V^*{}_{dse} \\ V^*{}_{qse} \end{bmatrix} = \begin{bmatrix} K_1 & -\left(K_{p1} + \dfrac{K_{i1}}{s}\right) \\ K_{p2} + \dfrac{K_{i2}}{s} & K_1 \end{bmatrix} \begin{bmatrix} i^*{}_{dse} - i_{dse} \\ i^*{}_{qse} - i_{qse} \end{bmatrix}. \quad (8)$$

Model of energy transmission system

Energy transmission system is composed of transmission line 1 and transmission line 2 models. V1 voltage can be obtained from eq. (1) and (2) as in eq. (9) and (10).

$$V_{1d} = -R_s i_d - \frac{x_s}{\omega_b}\frac{di_d}{dt} + x_s i_q + V_{sd}, \quad (9)$$

$$V_{1q} = -R_s i_q - \frac{x_s}{\omega_b}\frac{di_q}{dt} - x_s i_d + V_{sq}, \quad (10)$$

where i_d and i_q are the d-q components of the currents of shunt and series branch, transmission line and load currents. V_{sd} and V_{sq} are the d-q components of the source voltage.

Transmission line 2 is modeled by using eq. (6) for calculation of I_{se} current.

Load model

The load is expressed mathematically in eq.(11-12). In that equation load is represented as a voltage dependent power consumer [10]:

$$I_L = \frac{\left(P_L \pm jQ_L\right)}{V^*{}_{load-bus}}, \quad (11)$$

$$\begin{cases} P_L = fP(|V_{load-bus}|), \\ Q_L = fQ(|V_{load-bus}|). \end{cases} \quad (12)$$

Simulink model of the UPFC system

Simulink model of the UPFC system is modeled as subsystems in Matlab-Simulink by using system equations. This model can be explained according to the chart in Fig. 6. In this chart, the blocks related to UPFC are grouped under the UPFC model. In this system, the V_1 voltage which is obtained from transmission line 1 block, is compared with the value of the V_1 reference in UPFC model (shunt branch). I_{se} current which is calculated in block of the transmission line 2 is given to UPFC model (Series branch), and compared with the reference currents obtained from the active and reactive power references. According to the given active and reactive power references, UPFC model (Series brunch) produces a voltage of V_{se} and sends it to block of the transmission line 2. Shunt current (I_{sh}) and load current (I_L) are given to block of the transmission line 1. The same as the current I_{se} is obtained from the transmission line 2, has been sent to transmission line 1 block to provide the the current cycle of the transmission system. Subsytems of the simulink model have not been demonstrated due to space constraints.

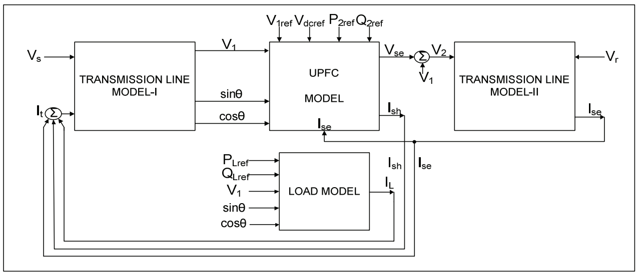

Fig. 6. UPFC system simulink model principle scheme

Simulation results

In order to observe the effect of UPFC on power system three simulations have been made. In first simulation UPFC acts as a STATCOM. Therefore this is the STATCOM mode of operation. V_{1ref}=1 pu. Load injected at t=0.15 sec. and rejected at t= 0.35 sec. As seen in Fig. 7. bus 1 voltage decreases and it approximately has value of 0.98 pu when P+jQ inductive load injected at t=0.15. Decreased bus 1 voltage is increased to 1 pu which is reference value, on short notice by controlling of UPFC bus 1 voltage. UPFC shunt converter provides reactive power to the system at interval of $0.15 \le t \le 0.25$ and operates in capacitive mode as seen in Fig. 9 and 10. This case means that the reactive power is supplied to the system. It has been seen that UPFC shunt reactive current (I_{qsh}) is positive at interval of $0.15 \le t \le 0.25$ correspondingly in Fig 8. P+jQ load is rejected at t=0.25. When P-jQ capacitive load injected at t=0.25 (Fig. 7) bus 1 voltage has increased approximately to 1.02 pu. Increased bus 1 voltage is decreased to 1 pu, which is reference value, with controlling of UPFC bus 1 voltage. UPFC absorbs reactive power from the system at interval of $0.25 \le t \le 0.35$ and operates in inductive mode as seen in Fig. 11. It has been seen that UPFC shunt current (I_{qsh}) is negative at interval of $0.25 \le t \le 0.35$ parallely in Fig. 8. P-jQ load is rejected at t=0.35. UPFC provides reactive power to the system at interval of $0.15 \le t \le 0.25$, but it absorbs reactive power from the system at interval of $0.25 \le t \le 0.35$ as seen Fig. 9–Fig. 11.

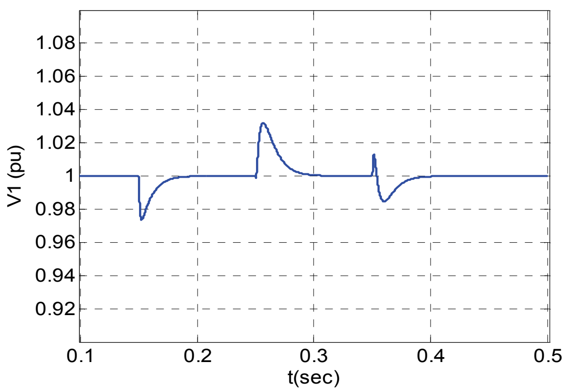

Fig. 7. Control of bus 1 voltage

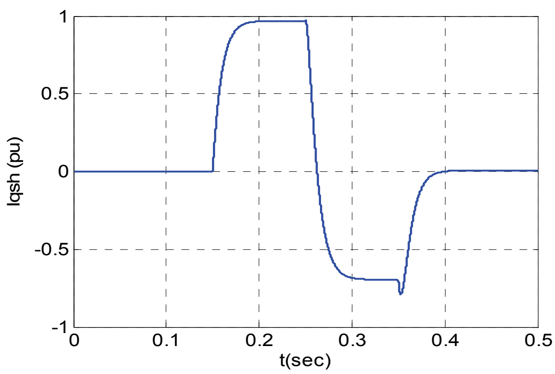

Fig. 8. UPFC Shunt branch reactive current

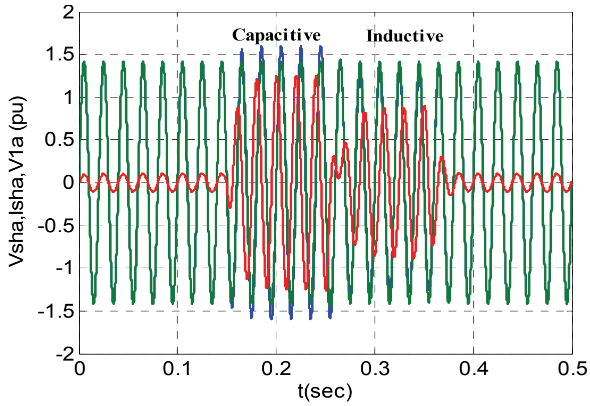

Fig. 9. Changing of Vsha, Isha and V1a

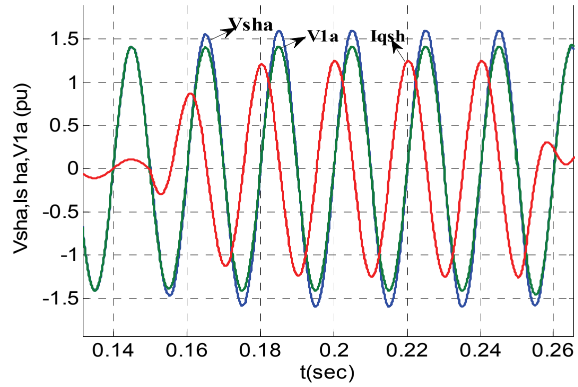

Fig. 10. Capacitive operation in the mode of STATCOM

In Fig. 12 changing of bus 1 reactive power flow is seen with controlling UPFC and without it. It is seen that bus 1 reactive power flow increased after load injected from this situation. But reactive power flow reduced with UPFC control. UPFC enhanced the transmitted active power as seen in Fig. 14. Changing of bus 1 voltage is comparatively seen with UPFC control and without it as seen in Fig. 13.

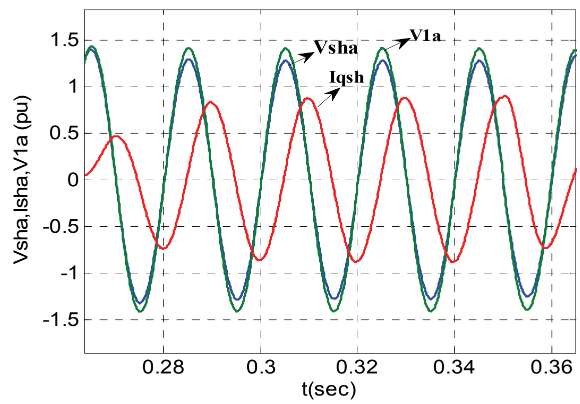

Fig. 11. Inductive operation in the mode of STATCOM

In second simulation UPFC controls the bus 2 active power and at the same time bus 1 voltage. UPFC is in automatic power flow control mode. P_{2ref}=3 pu and V_{1ref}=1 pu. Load injected at t=0.1 sec. and rejected at t= 0.3 sec.

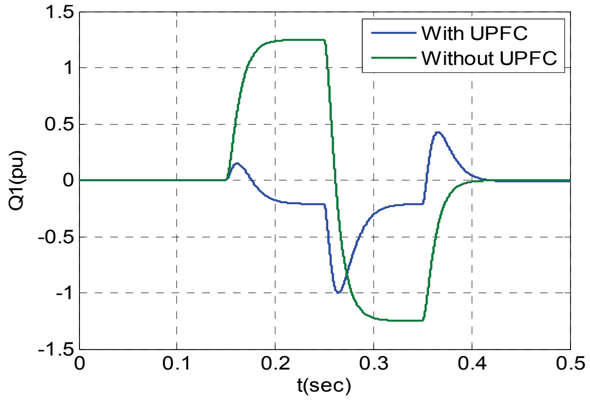

Fig. 12. Changing of bus 1 reactive power with and without UPFC

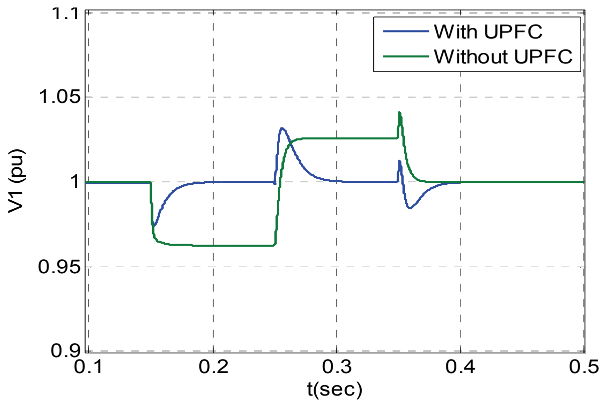

Fig. 13. Control of UPFC bus voltage with and without UPFC

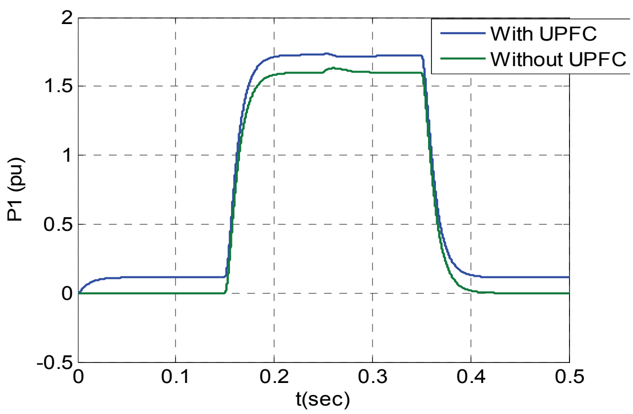

Fig. 14. Changing of bus 1 active power with and without UPFC

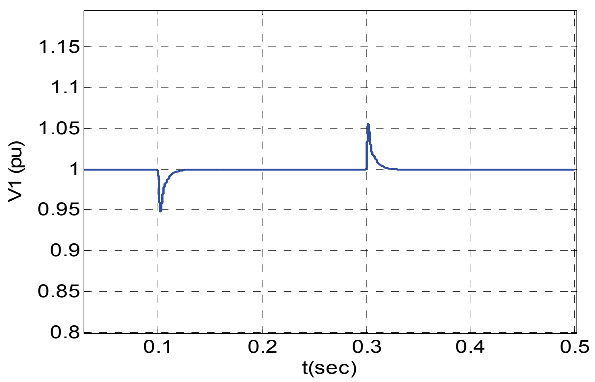

Fig. 15. Control of bus 1 voltage

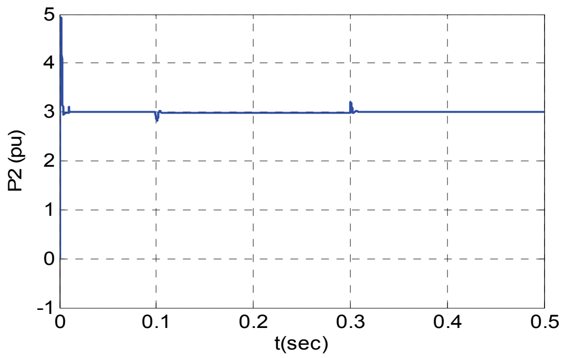

Fig. 16. Changing of transmission line bus 2 active power

Results are as follows; In this section, UPFC has a control of bus 2 active power at the same time it holds the bus 1 voltage stable at 1 pu. UPFC shunt converter operates in automatic voltage control mode.Active power flow of 3 pu is wanted to be formed at bus 2. Therefore, P_{2ref} is selected as 3 pu. P_2 active power reaches to its reference value initially given as seen in Fig. 16. Series converter injects voltage for providing given reference value to the system. P_2 active power has short time changes when load injected and rejected. But P_2 active power has its reference value in a short time. Bus 1 voltage has decreased to value of 0.95 pu when load is injected at t=0.1 as seen in Fig. 15.

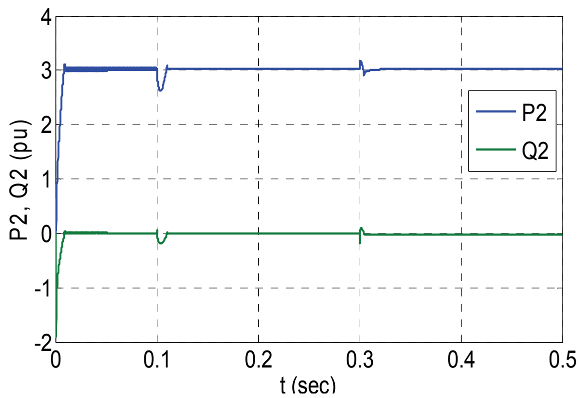

Fig. 17. Changing of transmission line active and reactive power

In the third simulation it is seen that system has $P_{2ref}=3$ ve $Q_{2ref}=0$ values via UPFC in Fig. 17. In this situation, UPFC hold the system in unit power factor. Being in unit power factor of system enables to be transmitted maximum active power quantity. This results in the most efficient usage of transmission line in terms of thermal limit.

Conclusions

In this paper, the dynamic analysis of UPFC is performed. Analysis is about the investigation of capability of UPFC in voltage control and power flow control in power systems. In this purpose, an educational&industrial MATLAB-Simulink model is developed to use in the analysis of UPFC. It can also be used for other converter based FACTS devices. Developed model enables to investigate the effects of UPFC to power systems. For this reason model is simple and useful. Model is performed with equations that obtained at the d-q frame of reference. Cross-coupling control method is preferred for series voltage injection due to its superiority from the other methods. UPFC system which is a fundamental two machine system is modelled as subsystems in MATLAB/Simulink enviroment. In simulation studies, basic properties of UPFC such as terminal voltage regulation (shunt part) and automatic power flow control is investigated in detail. Simulation results shows that UPFC can control both active and reactive power and the bus voltage which UPFC is connected across the transmission line independently. Results demonstrate that voltage control, active and reactive power control in energy transmission systems, can be effectively carried out with UPFC .

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M. M. Ertay, Z. Aydogmus. The Simulation Study and Dynamic Analysis of Unified Power Flow Controller for Industrial and Educational Purposes // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 5(121). – P. 109–114.

Unified Power Flow Controller (UPFC) is versatile and one of the advanced FACTS devices. In this study, dynamic analysis of UPFC is realized by MATLAB-Simulink simulation. For this purpose, a simulation model is presented that enable to be analysed of effects of device to power system in detail. Simulation model is a based on shunt current injection and series voltage injection. UPFC system dynamic model is based on a d-q synchronous reference frame. Developed simulation model enables to be analyzed effects of UPFC and the other converter based FACTS devices (STATCOM, SSSC,IPFC) to power system very simply. Besides, it can be used for education purpose in graduate studies which is about converter based FACTS devices. On the other hand, it can be used for industrial purpose in terms of power system engineers' investigations of effects of UPFC to power system. Simulated UPFC system consists of a load, UPFC and a power system with two machines. In simulation studies, functions of UPFC such as terminal voltage regulation and automatic power flow control is analysed and results are presented in case of graphics. Ill. 17, bibl. 18 (in English; abstracts in English and Lithuanian).

M. M. Ertay, Z. Aydogmus. Unifikuoto galios srauto valdiklio skirto pramonei ir edukacijai, modeliavimas ir dinaminė analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 109–114.

Unifikuotas galios srauto valdiklis (UGSK) yra universalus ir vienas iš pažangiausių lanksčių elektros perdavimo sistemų įtaisų. UGSK dinaminė analizė atlikta modeliuojant MATLAB-Simulink. Modelis pagrįstas šunto srovės injekcija ir impulsų eilės įtampos injekcija. Sukurtas modelis leidžia analizuoti UGSK ir kitų perdavimo sistemos įtaisų efektus. Be to, jis gali būti naudojamas mokomaisiais tikslais studijuojant elektros perdavimo sistemų konverterius. Il. 17, bibl. 18 (anglų kalba; santraukos anglų ir lietuvių k.).