DSP-BASED IMPLEMENTATION OF A SINGLE PHASE UPFC


*Electrical Power and Machines Dept., Faculty of Eng., Mansoura University, Mansoura, Egypt
**Electrical Power and Machines Dept., Faculty of Eng., Tanta University, Tanta, Egypt

Abstract: In this paper, Digital signal processor (DSP)-based implementation of a single phase unified power flow controller (UPFC) is presented. An efficient UPFC control algorithm is achieved for both shunt side and series side. Two H-bridge PWM voltage source converters linked by DC source are taken as an UPFC. The experimental results of a laboratory prototype are given and discussed.

1. INTRODUCTION

Flexible AC Transmission Systems (FACTS) is the recent technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability and thermal limit. One FACTS controller in particular, the Unified Power Flow Controller (UPFC), is capable of concurrently or selectively controlling transmission line impedance, voltage magnitudes and phase angles in a power system. The UPFC brings major benefits in steady state operation of power systems as well as in emergency situations [1]. The main function of the UPFC is to support voltage and control power flow [2, 3].

Voltage support and power flow control through UPFC is gaining wider acceptance due to advancements in power electronics and microelectronics technologies. References [2, 3, 4] and others concentrated on the computer simulation of UPFC. A hardware setup of UPFC and its control system is needed to complement the research process.

Nowadays, the use of Digital signal processor (DSP)-based control of power conversion circuits and systems has enabled simplification of digital control hardware for improved reliability and lower sensitivity to environmental effects such as temperature, supply voltage fluctuations and aging of components. DSP-based control has greater flexibility as compared to other methods, because all the control algorithms are implemented in software [5]. References [5, 6, 7] implemented other FACTS devices using DSP. In [5], DSP-controlled active-switch power factor correction converter system have been described. In [6, 7], the multifunctional capabilities DSP-based STATCOM are covered. In this paper, the UPFC is implemented to verify its function in laboratory and discover its practical problems.

This paper presents a new closed loop and instantaneous adaptive control algorithm of a single phase UPFC. The proposed algorithm is based on the active power filter (AF) reference current calculation found in [8, 9, 10]. The UPFC is connected to the mid-point of a single phase transmission line. Experimental results are given, which verify that the DSP-based control system enables the proposed control method to be efficient.
2. UPFC BASICS

The basic operation of the unified power flow controller was described in [1, 3]. The UPFC consists of two switching converters operated from a common dc link, as shown in Fig. 1. Converter 2 (series converter) performs the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line. The basic function of Converter 1 (shunt converter) is to supply or absorb the active power demanded by Converter 2 at the common dc link. This is represented by the current $I_p$. Converter 1 can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. This is represented by the current $I_q$.

3. NEW UPFC CONTROL ALGORITHM

The proposed control algorithm is based on the active power filter reference current calculation [8, 9, 10].

Without UPFC shunt compensation, the line current, which is consisted of active and reactive components, made up of the following terms: (neglecting the dc and harmonic components)

$$i(t) = i_p(t) + i_q(t) = I_p \sin(\omega t) + I_q \cos(\omega t) \quad (1)$$

Where:

- $i_p(t)$ in phase line active current of the T.L
- $i_q(t)$ reactive current of the T.L

To regulate the voltage at bus connected to the shunt converter of the UPFC, the only component that this bus should supply is the active current component. Using eqn. (1), it can be noted that if the shunt converter of the UPFC supplies the reactive component, then the sending bus needs only to supply the active component as shown in Fig.1. This can easily accomplished by subtracting the active current component from the measured line current.

$$i_q(t) = i(t) - I_p \sin(\omega t) \quad (2)$$

In eqn. (2), $I_p$ is the magnitude of the in-phase current (to be estimated) and $\sin(\omega t)$ is a sinusoidal in phase with the line voltage. The circuit shown in Fig. 2 can accomplish this operation. The estimation of $I_p$ is explained as:

Consider the product of the line current of eqn. (1) and a sinusoid in phase with the line voltage.

$$i(t) \cdot \sin(\omega t) = \frac{I_p}{2} [1 - \cos(2\omega t)] + \frac{I_q}{2} \sin(2\omega t) \quad (3)$$

After the multiplication, the only dc term in eqn. (3) is proportional to $I_p$. Thus, a low-pass filter whose cutoff frequency is below $\omega$ permits to obtain $I_p$ which is an estimation of the magnitude of $i_p(t)$. Then, this dc value is multiplied by the same in-phase sinusoid, obtaining an estimation of the instantaneous active current $i_p(t)$. Finally, this value of $i_p(t)$ is subtracted from the measured line current obtaining the reactive current $i_q(t)$ injected to the power system.

The mentioned method is an open loop implementation and has some problems. These problems were overcome by using the closed loop system shown in Fig. 3.
single phase AC supply 220 volt, 50 Hz. The voltage and current signals are taken from the mid-point of the transmission line and scaled using LV (divided by 73.0) and LA (divided by 1.0), respectively. These signals are the input of the control system, shown in Fig. 5, through analogue to digital input channels of the DSP. The DSP input channels divide the input signals by 10.0. The PWM four signals are isolated using optocoupler circuit. These signals are the gate signals of the eight MOSFETs, constructing shunt and series converters (H-bridge 1 and H-bridge 2). Each signal switch on two MOSFETs in the same time. The output of each converter is illustrated in an oscilloscope. The output of shunt converter is the input of shunt transformer, which injects reactive current to the mid-point of the system.

Fig. 3. Closed-loop modified system for UPFC shunt injected current

4. SYSTEM CONFIGURATION AND CONTROL

Figure 4 shows the system configuration of a single phase UPFC and its control system. The single phase transmission line model is fed from a
Fig. 5. (a) Control algorithm of a single phase UPFC and (b) PWM subsystem

The output of series converter is the input of series transformer (boosting transformer) which adds a series injected voltage to the mid-point voltage. Elements of the system are found in the Appendix.

5. PERFORMANCE OF UPFC

The UPFC is tested on laboratory for both shunt and series converters. The test results are shown in figures (6 – 15), and the values of all the quantities shown in these figures are given for two cases. Case 1 for light load and case 2 for heavy load.

Figures 6 and 7 show the phase relationships between the measured input voltage and the shunt converter control waveforms, and between the measured input current and the series converter control waveforms for cases 1 and 2, respectively.

Now, the converters’ output is an important issue. In case 1, for light load of 244 mA, the measured input voltage is 204.4 V and leads line current by 72°. This phase shift is shown in fig. 6. The output voltage of the shunt converter has a 70 V (fixed) peak value and leads the input voltage by 90° as shown in Fig. 8. The value of shunt converter peak voltage can be controlled according to the required injected reactive current and this is left for the future work. In Fig. 9, the output voltage of the series converter leads the line current by 216° (or leads the measured voltage by 144°).

In case 2, for heavy load of 1.4 A, the waveforms of Fig. 10 show that the measured input voltage decreased to 153.3 V. The shunt converter output voltage is still leads the measured voltage by 90°. Figure 11 shows that the series converter output voltage leads the line current by 36°. Also, the magnitude of the series injected voltage can be adjusted by controlling the DC supply (link).

The output of each converter is injected to the mid-point of the simple power system throughout voltage transformer. Figures 12 and 13 show the voltage of point connecting the UPFC for cases 1 and 2, respectively. The voltage is increased to 219 volt for case 1 and reached 201 volt for case 2. Figures 14 and 15 show the mid-point voltage after adding the series injected voltage for both cases.
Fig. 6. Measured input voltage (v), input current (i), shunt converter control and series converter control waveforms for case (1)

Fig. 7. Measured input voltage (v), input current (i), shunt converter control and series converter control waveforms for case (2)

Fig. 8. Output voltage of the shunt converter and measured input voltage waveforms for case (1)

Fig. 9. Output voltage of the series converter and measured input current waveforms for case (1)

Fig. 10. Output voltage of the shunt converter and measured input voltage waveforms for case (2)

Fig. 11. Output voltage of the series converter and measured input current waveforms for case (2)
6. CONCLUSION

Digital signal processor (DSP) – based single phase unified power flow controller (UPFC) has been implemented. A simple and efficient UPFC control algorithm has been achieved for both shunt side and series side. This algorithm is based on the active power filter current reference calculation method. The PWM voltage source converters linked by DC source have been taken as an UPFC. The experimental results have been analyzed. The shunt converter output voltage is found in quadrature with the bus voltage connecting UPFC and achieves voltage support. The series converter output voltage leads line current by an angle dependent on the required power flow in the line which includes the UPFC. The effect of series converter control is clear in large scale power systems because it can control the amount and direction of power flow between different buses. The problem of harmonics found in the injected waveforms is due to the voltage transformer. This problem can be avoided practically by using suitably designed shunt and series transformers.
7. APPENDIX
The elements used in laboratory are:
PC Host, Windows98, Matlab6.1(R12.1)/Simulink, DSP-TMS320C31 Hardware, DSpaceR4.3 Software, 2 Single-Phase 250Km T.L. model, Single-Phase source (220 volt, 50 Hz), 2 Single-Phase 400 Watt / 300 Var variable (R-L) load, 1 LV25-P (400 V), 1 LA25-NP (25 A), Optoisolator circuit (4N35), Two H-bridges each consists of 4-power MOSFETs (IRFP460), Fixed 70 volt DC supply and single phase voltage transformer 220/57.7 volt.

8. REFERENCES