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Improved IUPQC Topology for Simultaneous Compensation of Voltage and Current in Adjacent Feeders

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Abstract: ***This paper proposes anew connection for a unified power quality conditioner (UPQC) to improve the power quality of two feeders in a distribution system. The interline custom power devices named Interline Unified Power Quality Conditioner (IUPQC) is improved for various power quality disturbances and modeled in MATLAB/SIMULINK by using fuzzy logic controller. The developed topology can be used for simultaneous compensation of voltage and current imperfections in a multibus/multifeeder system. the propped IUPQC is designed for medium voltage s (11kv). Enhanced Phase Locked Loop (EPLL) based control technique is used to detect and extract the PQ problems. The performance of series compensator of IUPQC is evaluated through extensive simulations for mitigating unbalanced voltage sags, voltage swells with phase jumps and interruption. The performance of shunt compensator of IUPQC is also used for harmonic and reactive power compensation that are not investigated before in literature. It is verified that IUPQC which is connected to two feeders can compensate current and voltage distortions successfully.***

Keywords: Interline Unified Power Quality Conditioner, Voltage source converter, Power Quality, Enhanced Phase Locked Loop

1.Introduction

Power quality has become an important factor in power systems, for consumer and household appliances with proliferation of various electric/ electronic equipment and computer systems. The main causes of a poor power quality are harmonic currents, poor power factor, supply voltage variations, etc. In recent years the demand for the quality of electric power has been increased rapidly. Power quality problems have received a great attention nowadays because of their impacts on both utilities and customers. Voltage sag, swell, momentary interruption, under voltages,overvoltages, noise and harmonics are the most common power quality disturbances

In recent years, the use of nonlinear and electrically switched devices that draw non-sinusoidal currents in to the power systems have increased in utility and thus contribute to the degredation of power quality. Power quality problems such as harmonics, voltage sag/swell, interruption, imbalance, transients and flicker have become serious concern for both electric utility companies and electric power consumers. On the other hand, an increase of sensitive loads involving digital electronics and complex process controllers requires a pure sinusoidal supply voltage for proper load operation

1.1 Power Quality

Electrical Power quality is the degree of any deviation from the nominal values of the voltage magnitude and frequency. From the customer perspective, a power quality problem is defined as any power problem manifested in voltage, current, or frequency deviations that result in power failure or disoperation of customer equipment.

The contemporary container crane industry, like many other industry segments, is often enamored by the bells and whistles, colorful diagnostic displays, high speed performance, and levels of automation that can be achieved. Although these features and their indirectly related computer based enhancements are key issues to an efficient terminal operation, we must not forget the foundation upon which we are building. Power quality is the mortar which bonds the foundation blocks.

Power quality also affects terminal operating economics, crane reliability, our environment, and initial investment in power distribution systems to support new crane installations. To quote the utility company newsletter which accompanied the last monthly issue of my home utility billing: 'Using electricity wisely is a good environmental and business practice which saves you money, reduces emissions from generating plants, and conserves our natural resources.' As we are all aware, container crane performance requirements continue to increase at an astounding rate. Next generation container cranes, already in the bidding process, will require average power demands of 1500 to 2000 kW – almost double the total average demand three years ago.

The rapid increase in power demand levels, an increase in container crane population, SCR converter crane drive retrofits and the large AC and DC drives needed to power and control these cranes will increase awareness of the power quality issue in the very near future.

1.2 Sources and Effects of Power Quality Problems

Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. While power disturbances occur on all electrical systems, the sensitivity of today's sophisticated electronic devices makes them more susceptible to the quality of power supply. For some sensitive devices, a momentary disturbance can cause scrambled data, interrupted

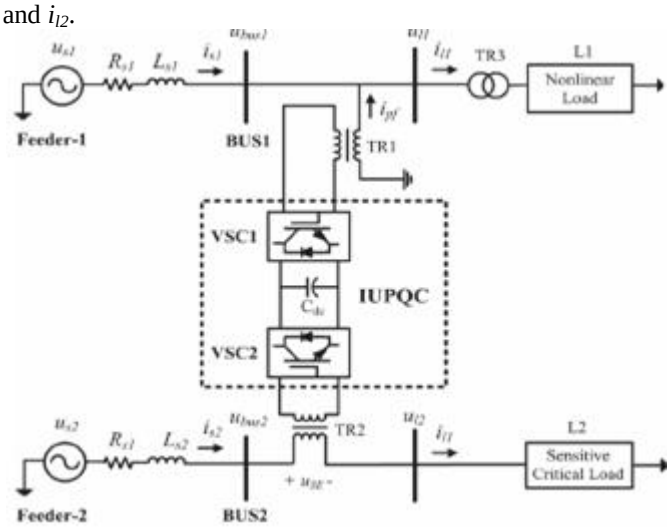
communications, a frozen mouse, system crashes and equipment failure etc. A power voltage spike can damage valuable components. Power Quality problems encompass a wide range of disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions.

- **Voltage dip:** A voltage dip is used to refer to short-term reduction in voltage of less than half a second.
- **Voltage sag:** Voltage sags can occur at any instant of time, with amplitudes ranging from 10 – 90% and a duration lasting for half a cycle to one minute.
- **Voltage swell:** Voltage swell is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min.
- **Voltage 'spikes', 'impulses' or 'surges'**: These are terms used to describe abrupt, very brief increases in voltage value.
- **Voltage transients:** They are temporary, undesirable voltages that appear on the power supply line. Transients are high over-voltage disturbances (up to 20KV) that last for a very short time.
- **Flickers:** Visual irritation and introduction of many harmonic components in the supply power and their associated ill effects.
- **Harmonics:** The fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency.

2.Design IUPQC

A. System Description

The structure of the IUPQC connected to a distribution system is shown in Fig. 1. As shown in this figure, the feeder impedances are denoted by (R_{s1}, L_{s1}) and (R_{s2}, L_{s2}). It can be seen that two feeders Feeder-1 and Feeder-2 are connected to two different substations that supply the system loads L1 and L2. The IUPQC is connected to two buses BUS1 and BUS2 with voltages u_{bus1} and u_{bus2}. The supply voltages are denoted by u_{s1} and u_{s2} while load voltages are denoted by u_{l1} and u_{l2}. Finally, two feeder currents are denoted by i_{s1} and i_{s2} while load currents are denoted by i_{l1} and i_{l2}.



The IUPQC consists of one series and one shunt converter which are connected to two adjacent feeders with being supplied from a common DC link. This topology provides power transfer between two adjacent feeders through DC link and it is very advantageous instead of conventional UPQC topology in a single feeder. In the proposed con¿guration, VSC1 is connected in parallel with load L1 at the end of Feeder-1 and VSC2 is connected in series with BUS2. The aims of the IUPQC are listed below:

1)to compensate for reactive and harmonic components of nonlinear load current (i_{l1});
2)to regulate the load voltage (u_{l2}) against sag/swell, interruption and disturbances in the system to protect the sensitive/critical load L2.

In order to achive these two goals, shunt VSC (VSC1) operate as a current controller while the series VSC (VSC2) operate as a voltage controller.

B. Power Circuit Configuration

The IUPQC shown in Fig. 1 consists of two VSCs (VSC1 and VSC2) that are connected back to back through a common dc capacitor (C_{dc}). In this topology VSC1 is connected in shunt to Feeder-1 while the VSC2 is connected in series with Feeder-2. The components of shunt compensator power circuit are DC link capacitor, three-phase inverter circuit and smoothing inductor ($L_{f,apf}$) as shown in Fig. 2.

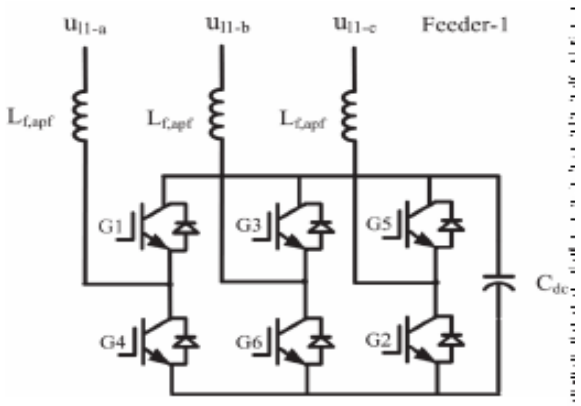


Figure 2. The schematic structure of Shunt VSC (VSC1)

Three-phase three-wire voltage source inverter topology is used as shunt compensator in this study. The smoothing inductors establish a link between VSC1 and power system. inductors convert VSC voltage to current and Smoothing allow shunt compensator to act as a current source. DC capacitor (energy storage unit) supplies required power for harmonic compensation of load current during operation. DC link voltage must be higher than the peak value of the utility voltage; otherwise the generated compensation currents cannot be injected to the power system. The shunt compensator must be connected to 11 kV level via transformer because of the limits of power semiconductor devices in VSC. The components of series compensator power circuit are DC link capacitor, inverter circuit, inverter side filter and injection transformer as shown in Fig. 3.

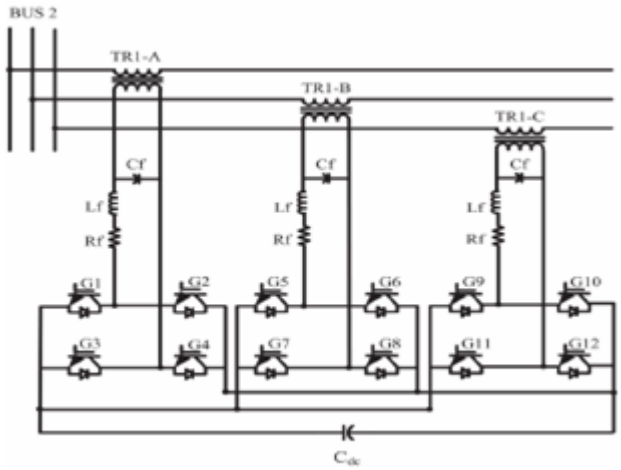


Figure 3. The schematic structure of Series VSC (VSC2)

Three single -phase H-Bridge voltage source inverter topology is used as series compensator in this study. Use of single-phase H-bridge PWM inverters makes possible the injection of positive, negative and zero sequence voltages. Thus, H-bridge PWM switched inverters provide superior performance to control asymmetries during unbalanced faults. The Series Compensator of IUPQC are connected to the distribution system in series through single phase injection transformers. The injection transformer primary winding is connected with series compensator power circuit while its secondary winding is connected in series with the distribution line. The main purpose of the injection transformer is to boost the voltage supplied by the filtered VSC output to the desired level while isolating the Series Compensator circuit from the distribution network [12]. In this study, LC type inverter side filter is used to attenuate the high-order harmonics generated by the voltage source inverter. Inverter side filtering scheme has the advantage of being closer to the harmonic source thus high-order harmonic currents are prevented to penetrate in to the series injection transformer thus necessitates a lower rating on the injection transformer [13].

C. Control Strategy

The IUPQC consist of Shunt and Series VSC which are controlled independently. The switching control strategy for series VSC and the shunt VSC are selected to be sinusoidal pulsewidth modulation (PWM) voltage control and hysteresis current control, respectively. In this study, simple and effective control algorithm is used to detect and extract the PQ disturbances. The algorithm is based on the nonlinear adaptive filter named Enhanced Phase Locked Loop (EPLL) presented in [14]. The reason of preferring EPLL is that it has simple structure than most preferred time based and frequency based methods and it has fast and accurate response with changing load conditions.

The EPLL is inherently adaptive and follows variations in amplitude, phase angle and frequency of the input signal. The EPLL is capable of accurately estimating the fundamental component of a polluted signal. The structure of the EPLL shown in Fig. 4, is simple and this makes it suitable for real-time embedded applications for software or hardware implementation [15]. The EPLL is formed from three main parts as shown in Fig. 4. These mainparts are phase detector (PD), low pass filter (LPF) and voltage controlled oscillator (VCO). The EPLL receives the input signal *u(t)* and provides an on-line estimate of the following signals:

- The synchronized fundamental component, *y(t)*;
- The amplitude, *A(t)* of *y(t)*;
- The difference of input and synchronized fundamental component, *e(t)*;
- The frequency deviation, *ǻw(t)*;

The phase angle *ș(t)* of *y(t)*.

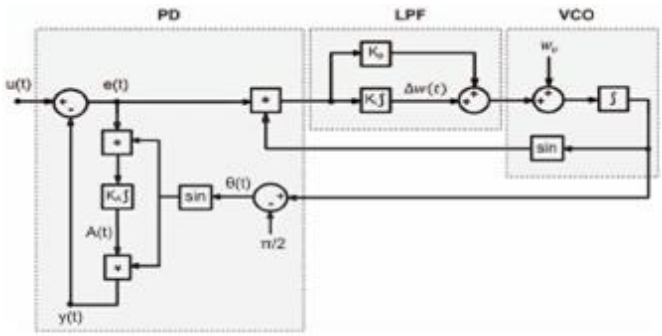


Figure 4. The structure of EPLL and its parameters

Mathematically, the EPLL is described by three main differential equations in time domain:

$$A(t) = \int e(t).\sin\theta(t).K_A.dt \quad (1)$$

$$wt = \int e(t).\sin(\theta - \pi/2)(t).K_i.dt \quad (2)$$

$$\theta(t) = -\pi/2 + [e(t).\cos\theta(t).K_p + wt + w_o]\,dt \quad (3)$$

The error signal, $e(t) = u(t) - y(t)$, is the total distortion signal of the input and can be expressed as a continuous time;

$$e(t) = u(t) - \sin\theta(t) \int e(t).\sin\theta(t).K_A.dt \quad (4)$$

K_A, K_i and K_p are gains and time constants of integrals that can affect the lock time of loop, amplitude estimation time and phase accuracy of input signal [15].

Functions of the shunt VSC (VSC1) are to compensate for the reactive component of load L1 current (i_{l1}), to compensate for the harmonic components of i_{l1} and to regulate the voltage of the common dc capacitor (V_{cap}). The controller algorithm of shunt compensator is formed from the harmonic current extraction, hysteresis current controller, DC link voltage controller and reactive power control as shown in Fig. 5.

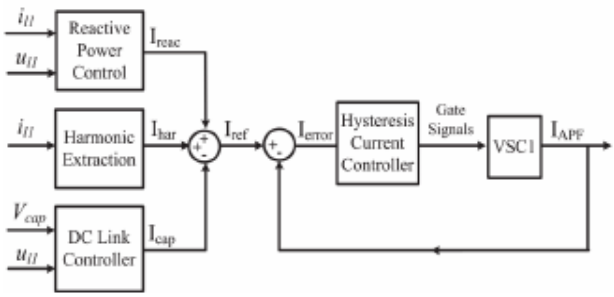


Figure 5. The control algorithm of Shunt Compensator

Shunt Compensator control system measures the load voltages (u_{l1}), dc capacitor voltage (V_{cap}), load currents (i_{l1}) and injected currents (I_{APF}). The controller processes the measured values and generates the required compensation signals. These signals are then compared in hysteresis controller and the required gate signals are generated.

When the distorted current or voltage signal is applied to EPLL, the harmonics and interharmonics of distorted signal (I_{har}) can be obtained from the *e(t)* signal of EPLL. DC link voltage control is achieved by using PI controller. The input of the PI controller is the error between the actual capacitor voltage V_{cap} and its reference value $V_{cap,ref}$. In order to keep DC link voltage at a constant level, shunt compensator must draw active power by drawing current (I_{cap}) in phase with line voltage. To draw a current in the same phase with system voltage, phase information of system voltage ($j_{Vload)}$ must be known. This can be achieved by using EPLL. With using phase of system voltage, DC link control reference current signal is created by multiplying the PI controller output and sine wave created by phase information of system voltage. The block diagram of reactive power control used in control method of Shunt Compensator module (VSC1) is shown in Fig. 6 [15]. Two identical EPLL units are used for voltage and current signals. The top portion of the unit is used for voltage and the bottom portion is used for current signal processing. The link between the two parts is to calculate the fundamental reactive current component (I_{reac}).

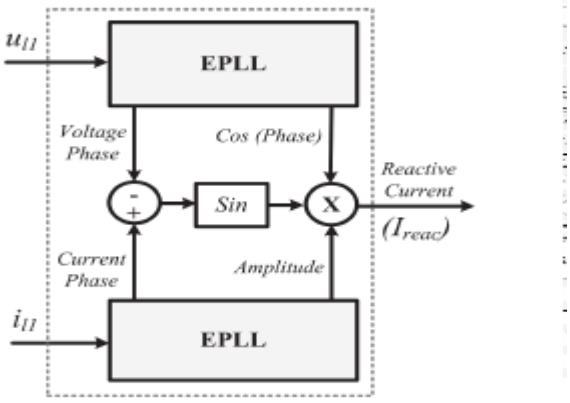


Figure 6. Block diagram of the proposed reactive-current extraction unit

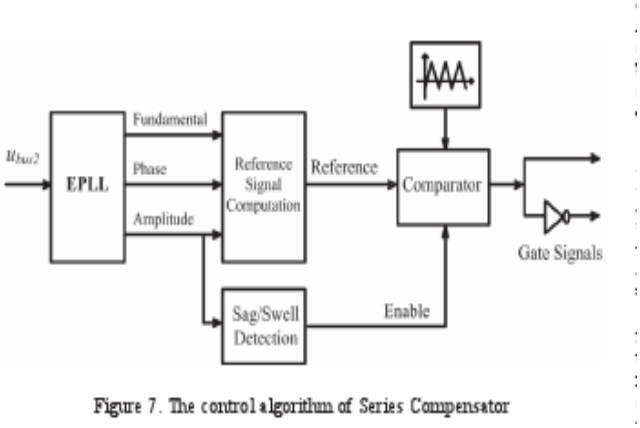


Figure 7. The control algorithm of Series Compensator

The main aim of the series VSC (VSC2) is to mitigate voltage sag/swell and interruption in Feeder-2. The control system of series compensator consists of sag/swell detection, reference voltage extraction and gate signal generation as shown in Fig. 7.

Simple and effective control algorithm is proposed for both sag/swell detection and reference voltage generation in this paper. The algorithm is based on the EPLL that extracts and directly provides the amplitude *A(t)*, phase angle *ş(t)* and fundamental component *A(t) cosş(t)* of the input signal for each phase independently. With the proposed method, the controller is able to detect balanced, unbalanced and single phase voltage sags/swells without an error. In this method, three EPLLs are used to track each of the three phases.

In the EPLL, the measured phase supply voltages are converted to per unit value. *A(t)* gives the amplitude of the tracked signal *u(t)*. If there is no sag or swell, *A(t)* signal is obtained as continuous 1 pu. By subtracting the *A(t)* signal from the ideal voltage magnitude (1 pu), the voltage sag/swell depth (S_{depth}) can be detected. The comparison of this value with the limit value of 10% (0.1 pu) gives information whether a fault occurred or not [16]. The voltage sag/swell detection based on EPLL method is presented in Fig. 8.

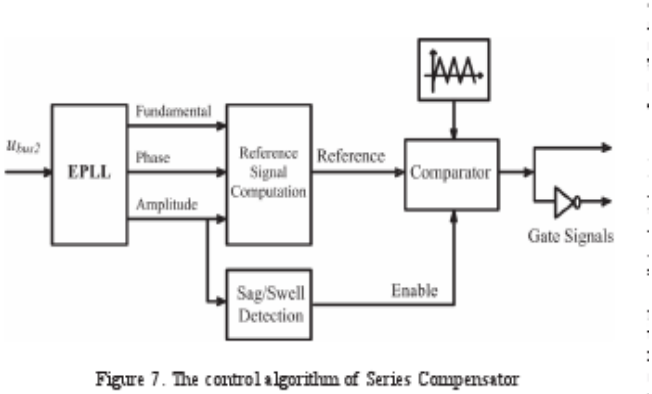


Figure 7. The control algorithm of Series Compensator

Reference voltage V_{error} is calculated according to voltage injection strategy by using magnitude *A(t)*, the output *y(t)* and Compensation method is used as voltage injection strategy. Pre-Sag Compensation (PSC) method tracks supply voltage continuously and if it detects any disturbances in supply voltage it will inject the difference voltage ($V_{error, presage)}$ between the sag or voltage at point common coupling

(PCC) and pre-fault condition, so that the load voltage can be restored back to the pre-fault condition.

If sag is accompanied by a phase jump, PSC method offers better performance by compensating voltage sags in the both phase angle and amplitude for sensitive loads [17]. Other voltage injection strategies such as in-phase, phase-advance and minimum energy injection compensation methods may not prevent the phase jump of the load voltage at the starting and ending instants of the sag compensation period [18].

PWM switching method is used as gate signal generation for series converter. The switching pulses are generated by comparing the reference voltage compensation signal V_{error} with a fixed frequency carrier triangular wave.

3.Simulation Results

The proposed IUPQC and its control schemes are tested through extensive case study simulations. In this section, simulation results obtained by PSCAD/EMTDC are presented, and the performance of the proposed IUPQC is analyzed. The system parameters of IUPQC system are provided in Table 1 and EPLL parameters are given in Table 2.

Table 1: System Parameters

System Parameters	Values
Fundamental Frequency (*f*)	50 Hz
Voltage Source (u_{s1})	11 kV (L-L, rms), phase angle 0^o
Voltage Source (u_{s2})	11 kV (L-L, rms), phase angle 0^o
Feeder-1 (R_{s1}+$j2\pi fL_{s1}$)	Impedance: 0,0015+j0,0785 ö
Feeder-2 (R_{s2}+$j2\pi fL_{s2}$)	Impedance: 0,0015+j0,0785 ö
Nonlinear Load (*L1*)	A three-phase diode bridge recti¿er that supplies a load of 100+j125.66 ö
Sensitive/Critical Load (*L2*)	150.0+j23.56 ö
DC Link Capacitor (C_{dc})	40 mF
DC Capacitor Voltage (V_{cap})	1700 V
Coupling Transformer (TR1)	2 MVA, 11/1 kV å/Y, Uk: 5%
Injection Transformer (TR2)	2 MVA, 1.2/8.0 kV, 10% Leakage reaktance
Power Transformer (TR3)	2 MVA, 11/6.3 kV å/ å, Uk: 10%

Table 2: EPLL Parameters

Parameters	Values
Integral Time Constant	0.02 s
K_A	500
K_i	30
Kp	300

A. Harmonic Distortion on Feeder-1

This case presents how VSC1 overcomes the load current harmonics with the proposed control algorithms. A three-phase diode bridge recti¿er is used as a harmonic current producing load. The nonlinear load contains lower and higher order harmonics with a total value of 25.08% THD before compensation. VSC1 eliminates the load current harmonics by injecting current that cancel harmonic currents of nonlinear load as shown in Fig. 9. The waveforms indicate the nonlinear load current (I_{l1}), its corresponding compensation current injected by VSC1 (i_{pf}), compensated Feeder-I current (i_{S1}) and the dc link capacitor voltage (V_{cap}) of Phase-A respectively. The results show that a successful reduction in harmonics of the nonlinear load current (i_{l1}) is obtained. A nonlinear load current with 25.08% THD is reduced to less than 5%. The PI controlled dc-link capacitor voltage is nearly kept at 1.7 kV.

B. Voltage Sag on Feeder-2

In this case, single line-to-ground unbalanced fault is considered, since it is most likely to occur in 70% of among all voltage sags in a distribution system [16]. 35% Single line-to-ground fault with 47.64o phase angle jump is investigated which occurs on Phase-A of BUS2 voltage between 0.3 s < t < 0.5 s. The sensitive/critical load (L2) voltage is not affected by voltage sag with the help of series compensator (VSC2). Fig. 10 shows the BUS2 voltage (u_{bus2}), series compensating voltage (u_{SE}), L2 load voltage (u_{l2}) and dc link capacitor voltage (V_{cap}).

C. Upstream Fault on Feeder-2

In this case study, the performance of VSC2 for upstream fault (interruption) mitigation on Feeder-2 is investigated. Single phase (L-G) interruption occurs on Phase- A of BUS2 voltage between 0.6 s < t < 0.8 s, and 25.27^o phase angle jump occurs during the interruption. The sensitive/critical load (L2) voltage is not affected by voltage sag with the help of series compensator (VSC2). Fig. 11 shows the BUS2 voltage (u_{bus2}), series compensating voltage (u_{SE}) and L2 load voltage (u_{l2}) and the dc link capacitor voltage (V_{cap}).

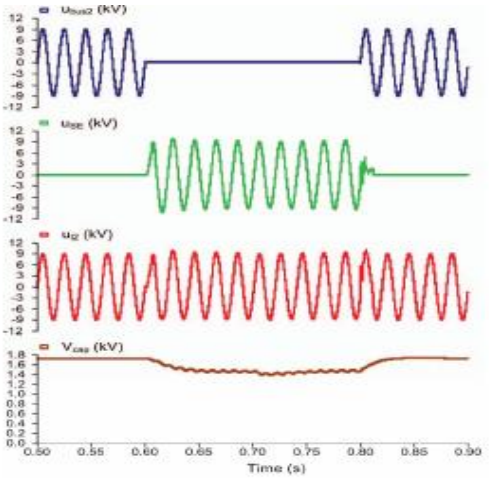


Figure 11. BUS2 voltage, series compensating voltage, load (L2) voltage and dc link capacitor voltage for Case C

4.Conclusion

In this paper, an improved IUPQC topology for simultaneous compensation of voltage and current in adjacent feeders has been proposed. An effective EPLL based control technique is used for IUPQC to detect and extract the PQ disturbances in multi-feeder system. Each phases of Series and Shunt Compensator are investigated independently with EPLL based controller. The performance of proposed IUPQC system is evaluated through extensive simulations for mitigating harmonics, unbalanced voltage sags with phase jumps and interruptions. The results of simulations show its effectiveness in handling these PQ issues, so that smooth and clean power flow to the loadsREFERENCES

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