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PV / Battery Scheme to Support 3-phase L.V. Grid by Compensating Reactive Power

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ABSTRACT
In the past few years the world has witnessed a rapid growth of PEV (Plug-in electric vehicles) market, Meanwhile the statistics indicates that by 2035 a total tentative number of 120 million PEV will encompass the roads Globally[1], Thus Kuwait eventually will have a share of that market, statistically Kuwait has an annual increment in passengers vehicle of 90,000 car/year , Therefore it is expected that by the year 2035 the PEV in Kuwait will reach a number of 10,000 units , especially if we know that Kuwait's kWh tariff is less than 0.01$, Hence the local power grid will be incurred with additional 0.5 GWh/year as a recharging energy for the same number of PEV's, Moreover this electrical energy growth will be accompanied with a significant impact of grid impedance, therefore this paper is intended to discuss a method to enhance the grid's power factor by an ancillary 3-phase grid tied bi-directional inverter to charge a battery bank along with a PV solar system to compensate grid's reactive power.

Keywords: Reactive power, PV solar system, Voltage sag, Plug-in electric vehicle.

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I. INTRODUCTION

The electrical energy burden is ramping up globally due to the extensive expansion of all technological aspects, mainly the G8 countries strive plan for electrifying the ground transportation (passenger vehicles) that will cause the world's electrical grid to sustain an additional 280 billion Wh by 2035 to fulfill the charging-energy demand when PEV's will reach a number of 120 million units as predicted by many statistical institutes, and to face this upcoming challenge all energy agencies and research entities are working diligently to optimize power generation systems which essentially requires improving power quality along with utilizing the different forms of renewable energies[2].

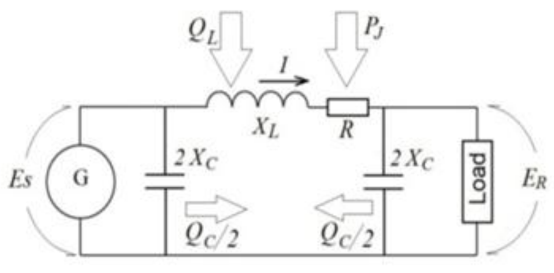

Fig. 1. Active and reactive power in a transmission line.

Power quality is all about diminishing energy losses and mainly grid impedance that caused by harmonics and reactance, reactance as known consist of two elements: Inductive reactance-X_L and Capacitive reactance-X_C, which both of them together causing grid resonant, in L.V. girds the impedance-Z is greatly induced by inductive reactance X_L and conductive resistance R_L , which are both resulting under-unity power factor (cos Θ), while in H.V. grid the capacitive reactance is also a significant element as illustrated in Fig. 1, in Kuwait The L.V. grid is heavily burdened by inductive loads during day peak hours at summer, Those inductive loads are mainly air-conditioning and cooling systems makes the average P.F. at L.V. segments around 0.87 ,where as the intended P.F. range is (0.95-1), therefore the aim of our proposed system is to provide a power factor displacement by 0.18 , the reactive power amount of course depending on the power magnitude consumed by grid segment which varies according to the type of loads and grid impedance and ambient temperature.

Kuwait in the past 6 years has commissioned a chain of ancillary projects to provide supermarkets and public car parking areas with PV solar sheds to generate A.C. power to the nearest premises, hence the proposed system is suggested to be attached to the same PV infrastructures but with more supportive functionality to the L.V. segments as shown in Fig. 2.

II. PV-BATTERY GRID-TIED COMPENSATING SCHEME

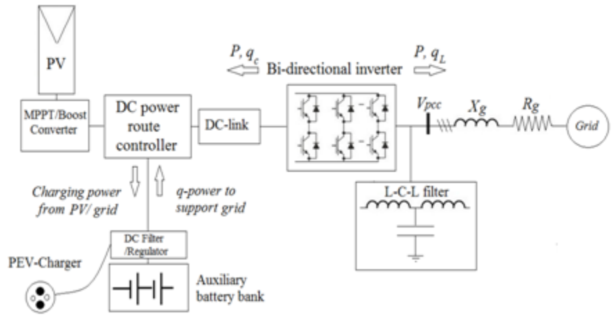

Fig. 2. PV/Battery scheme connected to the L.V. grid via a bi-directional 3-phase balanced inverter.

2.1. System's basic functionality

Our proposed system will be utilized to compensate the reactive power as well as charging the battery and supply the necessary energy to a PEV recharging station, Basically it will react as a PFI-capacitor (Power factor improving-capacitor) that works among 2 cycles: Absorb & release the reactive power, that means if the periodic reactive power phase is inductive-Q the compensating behavior of the system will have a capacitive effect q_C and the system will absorb the power as shown in Fig.3.

Consecutively when the periodic reactive power in capacitive phase the compensating behavior will have inductive effect (q_L) and the system will induce power to grid as per the A.C. power components which can be elaborated by the cyclic phases with loads (Fig. 4) that are divided into 4-quadrants over one full sinusoidal waveform (2π - 360^o).

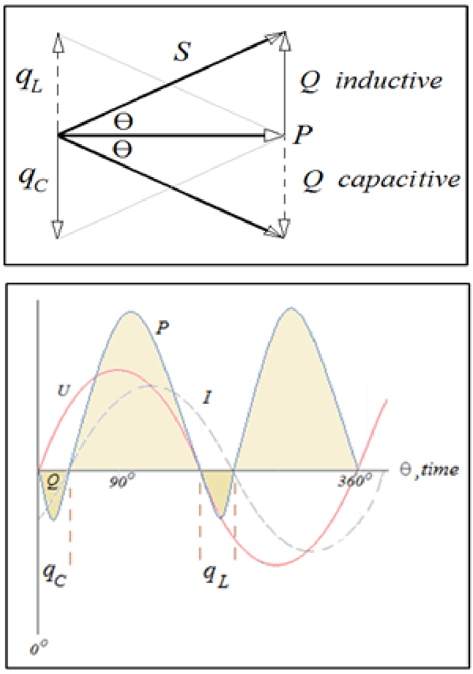

Fig. 3. Inverter's corrective response behavior (qL , qC) with respect to cyclic phases of reactive power.

The grid-tied bi-directional inverter is dealing with the effective power P and the reactive power Q, this functionality is based on the principle of minimizing the loss of apparent power caused by the reactive power Q as much as possible, so that the apparent power S is transformed fully to an effective power, and that requires eliminating the deviation angle Θ between voltage and current to capture optimally the RMS voltage value and respectively gaining a unity power factor instead of lagging or leading P.F., This dynamic behavior of the inverter is about importing & exporting Q-power.

The bi-directional inverter in this scheme will be fed by the existing PV setup (Average capacity 0.2 MVA) with an auxiliary battery bank, the PV setup will be used to maintain the battery bank at floating status, and meanwhile it will support the grid's stability through compensating the voltage sag caused by grid impedance-Z_g , the inverter will inject power to grid using *q* component of *dq*-transform during day hours while at night the battery bank will kick-in to support the grid voltage if needed via the inverter as well as supplying D.C. power to the PEV charging station that will be decided by D.C. power route controlling unit , meanwhile if the grid develop an excessive voltage ($V_{pcc} > V_{nominal}$) due to increasing transformer's tap changing or load-shedding, the bi-directional inverter will equalize the voltage by drawing a charging currents from grid for the battery bank or to supply PEV recharging station in order to negatively compensate the grid's reactive power (Fig.1).

2.2. Sizing the system

The L.V. grid segment's apparent power S that the system will be connected with is 0.2 MVA, but when designing a static reactive power correction system we should consider a minimum inverter's capacity to be equal to the maximum magnitude of reactive power of the grid segment's Q, therefore with reference to the average P.F. (0.87) the reactive power can be calculated as follow:

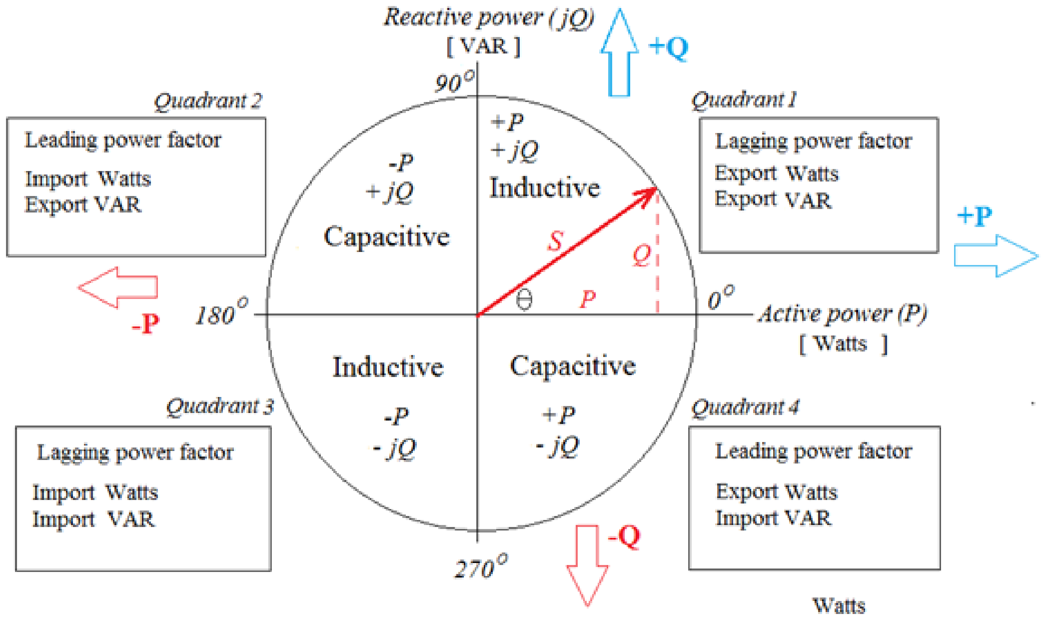

Fig. 4. Cyclic a.c. power component phases over 4-quadrants.

$$S = V * I * 1.73 \quad (1)$$

$$200\ kVA = 415 * I * 1.73$$
$$I = 278.6\ A$$
$$Q_{max} = V * I * 1.73 * \sin \Theta \quad (2)$$
$$Q_{max} = 415 * 278.6 * 1.73 * \sin (29.54^o)$$
$$Q_{max} = 98\ kVAR$$

, This compensation amount of Q-power can be mitigated into several inverters, and for more optimization their control units can be serially linked.

2.3. Bi-directional inverter

As known that the 3-phase grid-tied voltage source inverters (VSI) is using the *dq*-transform as dc components with the rotating unit ω to generate the SRF (Synchronous Reference Frame) which is employed by the inverter's control loop to respond dynamically with grid's power factor variation in order to improve power quality and efficiency (Fig. 5).

As illustrated in Fig. 6 the system will monitor the grid power stability by measuring the voltage at point of common coupling V_{pcc} and compute its deviation from Grid nominal voltage V_g, the amount of voltage sag is

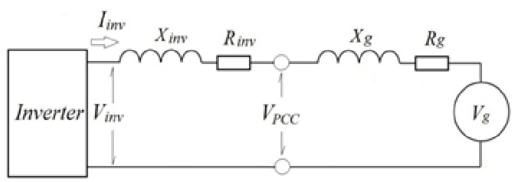

Fig. 6. L.V. grid / Inverter equivalent circuit.

dominated by grid impedance Z_g as follow:

$$V_g - V_{pcc} = I*Z_g \quad (3)$$

, If we neglect line resistance R_g , the equation can be expressed as:

$$V_g - V_{pcc} = I* \omega_g * L_g \quad (4)$$

The voltage sag factor x is equal to (V_{pcc} / V_g), with considering the dead band zone for x is (0.9 – 1.1) acting as a hysteresis gap, in the meantime I_q

magnitude generated by the inverter can be elaborated graphically by the (V_{pcc} , I_q) relation as represented in Fig. 7, which is dictated by the power factor correction element k angle δ which should be ≥ 2 with a rise-time < 20ms , as follow:

$$k = \tan \delta = I_q / (V_g - V_{pcc}) \quad (5)$$

, By using grid voltage value V_g , grid frequency f_g, grid inductance L_g, voltage sag factor x and real time power factor $\cos\Theta$ the control loop computes the required reactive power Q_{ref} to be generated as per the following equation:

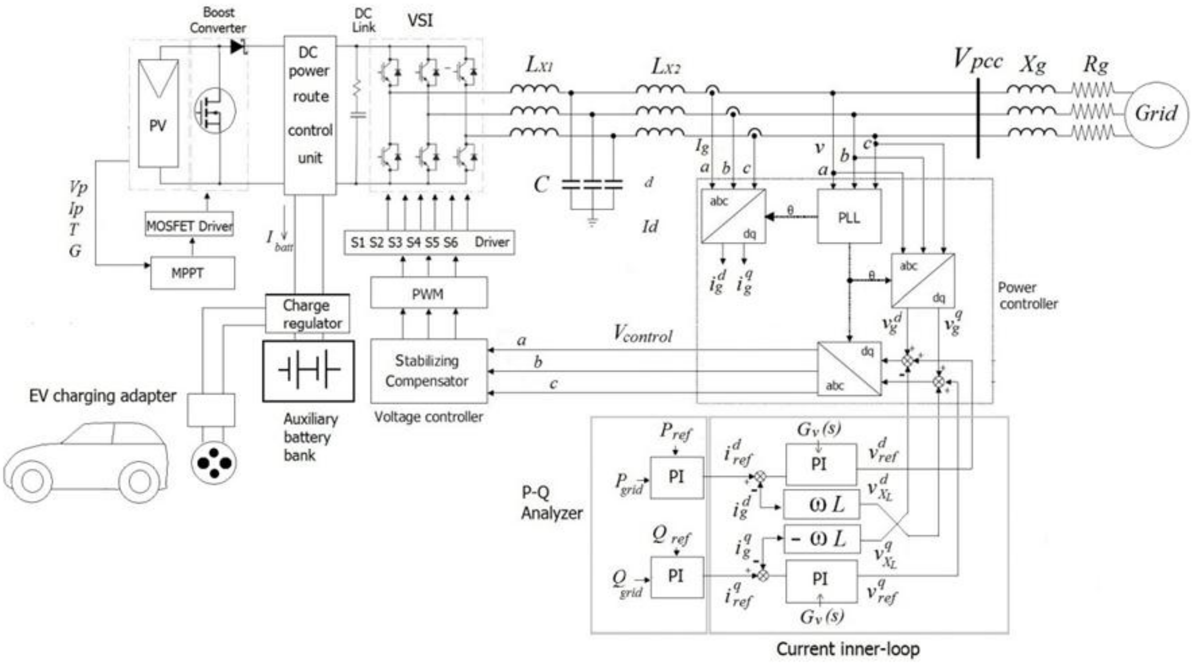

Fig. 5. Grid-tied inverter circuit block with PLL and P-Q control loops.

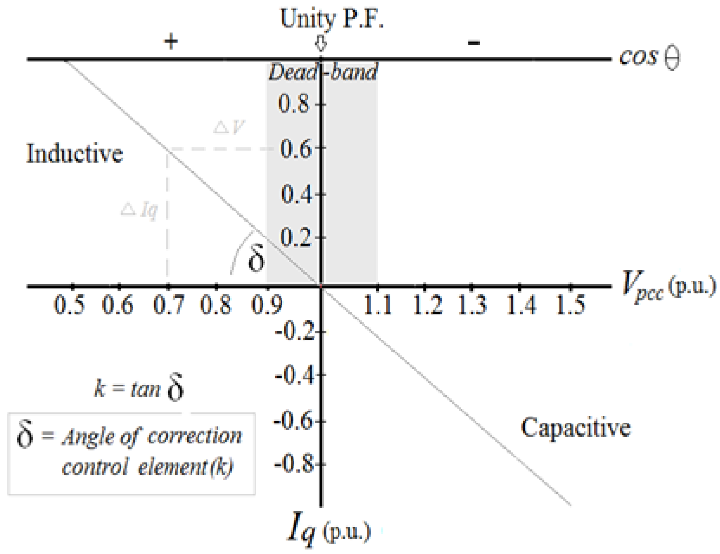

Fig. 7. Proportional Iq injection by inverter to the grid voltage sag.

$$Q_{ref} = [V^2_g /(2\pi f_g L_g)]*(1-x\cos\Theta) \quad (6)$$

, While the grid active power P_{grid} is computed as follow:

$$P_{grid} = v^d_g * i^d_g \quad (7)$$

The instantaneous grid reactive power Q_{grid} is used to calculate $Q_{control}$ by equation (11) and the result will be compared with reference value Q_{ref} which is used to determine the required value of I_q to the grid as follow:

$$Q_{grid} = (v^q_g * i^d_g) - (v^d_g * i^q_g) \quad (8)$$

, As the *dq*-transform is based on P-Q voltage oriented control method, thus the *q* axis is assumed to be aligned totally with *a*-axis of natural frame, and therefore the equation (8) can be summarized to the form represented in equation (9) after neglecting V_q value or consider it as a zero.

$$Q_{grid} = -(v^d_g * i^q_g) \quad (9)$$

The PLL unit will then extract the phase shift angle of the *dq*-transform by using the Laplace function $G_{PLL}(s)$ in the PI-unit (Fig. 8) to compute the voltage grid frequency f_o through multiplying angular speed ω of the voltage V_q by the time t to determine the *dq*-frame shift angle Θ_{out} with natural frame reference *(a-b-c)* considering the frequency set value f_r as a reference, the Θ value generated by PLL unit will be utilized by current & voltage *dq*-transform loops to determine power P and reactive power Q values and compare it to the reference value as follow :

$$P_{control} = P_{ref} - P_{grid} \quad (10)$$

$$Q_{control} = Q_{grid} - Q_{ref} \quad (11)$$

The P-Q controller is will provide the *dq*-transform voltage control commands to PWM via *dq/abc* interface including decoupling terms and feed forward of PCC voltage by using integration and proportional coefficients (K_i , K_p) as follow:

$$V^d_{cont} = v^d_g + [\, K_p + (K_i/s)\,] * (i^d_{ref} - i^d_g) - (\omega_g * L_g * i^q_g) \quad (12)$$

$$V^q_{cont} = v^q_g + [\, K_p + (K_i/s)\,] * (i^q_{ref} - i^q_g) + (\omega_g * L_g * i^d_g) \quad (13)$$

, Both equations can be summarized to the following forms:

$$V^d_{cont} = v^d_g + v^d_{ref} - v^q_g$$

$$V^q_{cont} = v^q_g + v^q_{ref} + v^d_g$$

, Given *dq* component of currents values (i^d_g , i^q_g) are calculated by equation (14) to be used with equations (12) and (13) to determine the value of V^d_{cont} and V^q_{cont} to be forwarded to *dq-abc* transforming unit in order to generate the PMW modulation control voltages V_a , V_b , V_c with a gate switching control gain factor k_{pmw} .

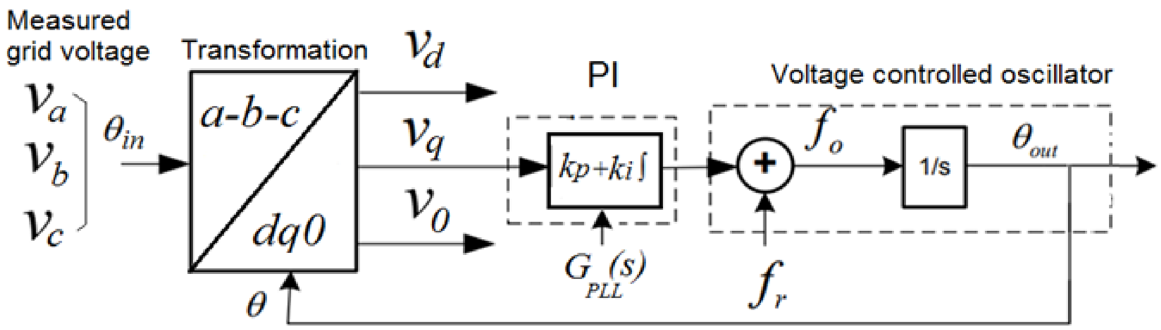

Fig. 8. PLL unit for 3-phase balanced system

$$\begin{pmatrix} i^d_g \\ i^q_g \end{pmatrix} = \frac{2}{3} \begin{pmatrix} v^d_g & v^q_g \\ -v^q_g & v^d_g \end{pmatrix}^{-1} \begin{pmatrix} P_g \\ Q_g \end{pmatrix} \quad (14)$$

III. SYSTEM FUNCTIONALITY SIMULATION

The grid-tied inverter with voltage support behavior by compensating reactive power can be simulated using MATLAB simulink, Specification of the grid, inverter, LCL filter, and controller are shown in Table.1, switching frequency is 6 kHz and rated apparent power is 10 kVA .

Table.1 Specification of Grid, Inverter, Filter and controller

Three-phase grid-tied inverter		
Line-to-line grid voltage	415	Vrms
Grid frequency, f_g	50	Hz
Grid inductance, L_g	1.25	mH
Grid resistance, R_g	0.5	Ω
Maximum grid current, THD_g	5	%
Switching frequency, f_{sw}	6	kHz
Output LCL filter		
Inverter side inductance, Lx_1	980	μH
Grid side inductance, Lx_2	430	μH
Parallel capacitor, C	25	μF
Resonance frequency, ω_{res}	1.83	kHz
Controller		
Proportional gain of dq-PI, K_p	5	Ω
Integral gain of dq-PI, K_i	60	Ω/s

To assess the control loop functionality the active power command in the inverter was set to -10 kW for the entire time range. Therefore we have designated three time intervals during inverter operation: a) During interval-1 from 0 s – 0.12 s grid voltage was stable without sag x , b) Interval-2 from 0.12 s -0.24 s voltage sag x = 0.8 was applied and detected by the inverter's control unit with inhibiting it's response, c) Interval-3 voltage sag was applied and the inverter compensate reactive power via inject I_q as per parameters with respect to the detected values.

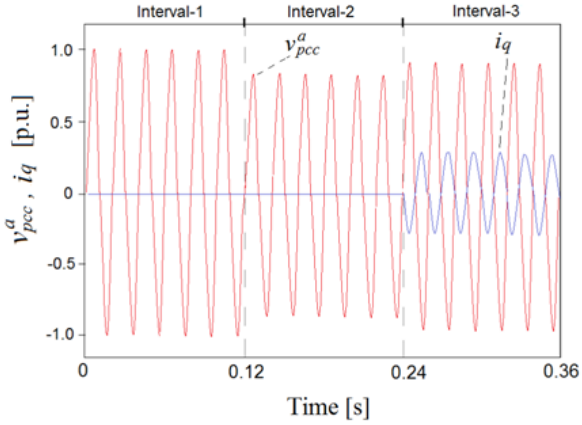

Fig. 9. Phase-a of *Vpcc* - *Iq* proportional values with reference to 0.8 p.u. voltage sag.

As presented in Fig.9 the v_{pcc} in interval-1 for phase-a was 1.0 p.u. (x = 1) , while during interval-2 a 0.8 p.u. voltage sag was simulated without Q-power compensation, at interval-3 the v_{pcc} was enhanced by approximately 10.2 % when i_q with a value of 0.27 p.u. was injected by the inverter to compensate Q-power.

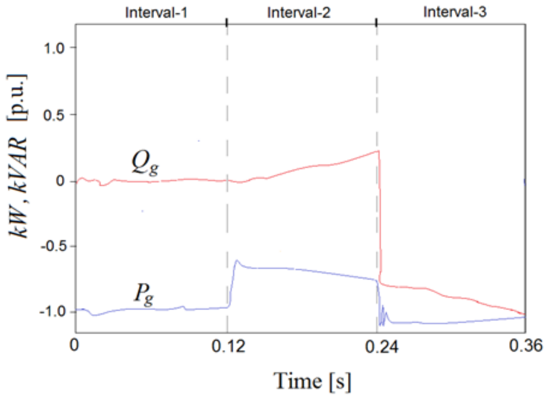

Fig. 10. Inverter's response to stabilize the active power *Pg* by compensating reactive power *Qg* with reference to 0.8 p.u . voltage sag.

The effect of Q-power compensation can be detected in Fig.10 on the declination of P.F. value due to the inductive effect in interval-2 caused by the increment in grid impedance-Z_g , but the nominal P.F. set value was almost restored in interval-3 by approximately 95% as plotted in the graphical behavior representation of grid active power P_g and reactive power Q_g in Fig.11.

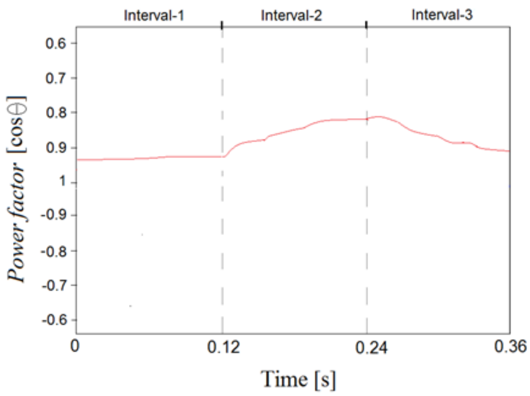

Fig. 11. Power factor correction with reference to 0.8 p.u. voltage sag.

IV. CONCLUSION

Modern grid-tied inverters has proved its corrective response by enhancing L.V. grid voltage stability and active power enhancement, the results has shown that a voltage sag of 0.8 p.u. in L.V. grid can cause approximately 60 % increment in Q-power when the P.F. declined by 11 % , Therefore PV systems should be primarily utilized as a large scale power factor improver in L.V. grid in Kuwait. ,Hence the ancillary power quality improving projects are essential in conserving electrical energy.

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