Power Exchanging Control of DG Units on Faulty Grid and Time-Varying Frequency Environments

M. Choopani, H. Askarian Abyaneh, S. H. Fathi, B. Ansari

Abstract—**This paper proposed a new power exchanging control under unbalanced-fault conditions. This new control method has been implemented directly in three-phase (*abc*) reference frame without any additional reference transform and provides independent control of active /reactive power. Furthermore the synchronization is used based on EPLL, which can adopt frequency quickly. Therefore, Transmission System Operators (TSO) can correctly ride-through disturbances occur in the system.**

Index Terms— **Fault Ride-Through, Unbalanced Voltages, Frequency-Dependent Power Control, EPLL**

I. INTRODUCTION

Recently, Distributed Power Generation Units (DPGUs) based on renewable energies contribute more and more to the total amount of energy production in the world. Among them, hydropower and wind energy have the largest utilization nowadays. In countries with hydropower potential, small hydro turbines are used to sustain the utility network at the distribution level. The wind power potential in many countries around the world has led to a large interest and fast development of wind turbines (WT) technology in the last decade. Photovoltaic (PV) is another renewable energy that its installed capacity increases day-by-day. However, it is worth noticing that the increased amount of distributed system connected to the utility network can create instability of the power systems, even leading to outages [1,2]. As a consequence, the transmission system operators (TSO) demand a participation of the DPGUs in additional grid services. These requirements are country dependent; only the standard IEC 61400-21 gives consistent frame of technical demands. Besides to this, the local utilities are free to issue other additional technical guidelines. Some basic features are:

- Frequency dependent control of the active power flow
- External control possibility of the active power by the TSO
- Grid voltage control by adjustable reactive power flow
- Unbalanced-Grid-Fault ride-Through during short circuits and unbalanced faults.

Fig.1 shows an example for some grid system services demanded by German transmission system operators. In Fig.1(a) the power curve over the frequency shown. DPGUs must not disconnect from the grid within the frequency range between 47.5 Hz and 51 Hz. The minimum duration of the power generation during grid frequency deviations is depicted in Fig.1(b); Fig.1(c) shows the voltage dependent reactive power supply [3].

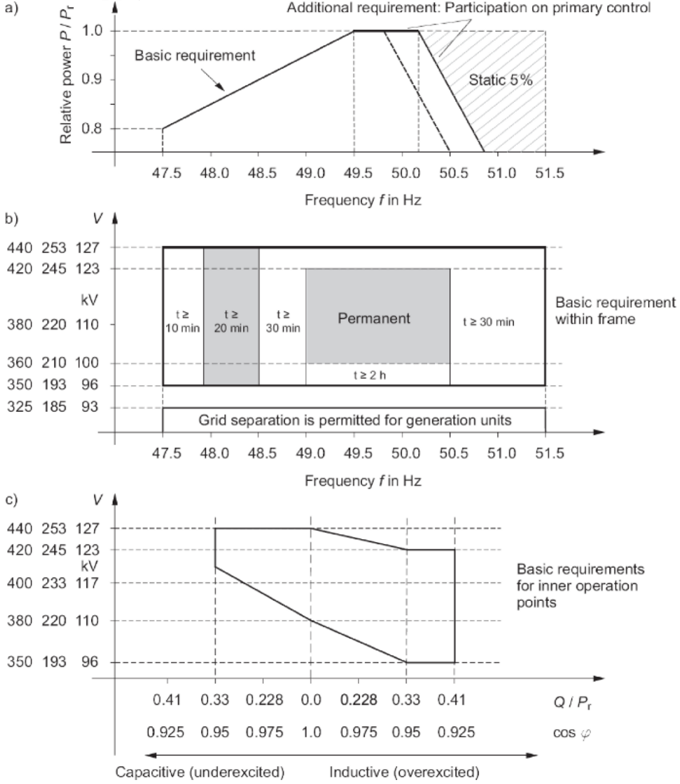

Fig. 1. Some grid services demand by German TSO [3].

II. UNBALANCED POWER EXCHANGING CONTROL

Usually, most of the faults occur in the grid are unsymmetrical. During an unbalanced fault, the grid voltages contain a significant negative-phase-sequence component, causing the derived current references to be time variant.

M. Choopani is with the Electrical Engineering Department of Amirkabir University of Technology, Tehran, Iran (corresponding author to provide phone: +98-21-64543370; fax: +98-21-66406469; e-mail: mahdi.choopani@gmail.com)
H. Askarian Abyaneh is with the Electrical Engineering Department of Amirkabir University of Technology.
S. H. Fathi is with the Electrical Engineering Department of Amirkabir University of Technology.
B. Ansari is with the Electrical Engineering Department of University of Tehran, Iran (ansaribx@gmail.com).

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Consequently, the voltage on the dc side and the power delivered to the grid will have a considerable second order harmonic due to interactions between the positive and negative sequence components of voltage and current [4].

Previous studies on modeling and control of the VSC under unbalanced conditions have suggested introducing the negative phase sequence into the current controller [5]. [5] proposed to implement a dual current controller, with one for the positive-sequence and one for the negative-sequence current. In this case, the complexity of the controller is high and positive and negative-sequence extraction is necessary. Nevertheless, using notch filter appreciably reduced the dynamic of the controller.

[6] proposed several stationary reference frame current controller, in order to independently control the active and reactive power delivered to the grid.

It should be noted that most of these the methods assume that the frequency is constant; therefore, frequency dependent control of the active/reactive power cannot be adopted (as said in the previous section). As a result, these methods may have a considerable error, when frequency changes. If this error is not compensated, it may lead to active/reactive power error and consequently may cause instability.

So, this paper has proposed a new method for independent control of active and reactive powers. The method has been directly implemented in the three phase *abc* system without any additional sequence extraction.

III. PROPOSED TECHNIQUE

Before having a discussion on the proposed technique, let us over the power characteristics under unbalanced conditions.

[4] proved that active and reactive powers can be written as:

$$\begin{cases} P(t) = P_0 + P_{c2}\cos(2\omega t) + P_{s2}\sin(2\omega t) \\ Q(t) = Q_0 + Q_{c2}\cos(2\omega t) + Q_{s2}\sin(2\omega t) \end{cases} \tag{1}$$

Only four of the power terms in (1) can be controlled through the converter currents: P_0, Q_0 must always be controlled for obvious reasons. P_c, P_s should be controlled because they represent instantaneous three-phase power oscillations, they must be zero in order to mitigate the dc voltages oscillation. Therefore Q_c, Q_s are not controlled, so the reactive power will be oscillatory with the average Q_0.

[7] proposed controlling of the active power directly in the three-phase (*abc*) reference frame. The main drawbacks of this can be stated as:

1) The zero sequence current has negative influence on the optimal active power control.
2) The average reactive power has not been controlled properly.

Therefore, this paper introduced new concepts to solve these problems efficiently.

The three-phase instantaneous power can be written as:

$$\begin{aligned} p(t) &= e_a\sin(\omega t+\phi_{ea})i_a\sin(\omega t+\phi_{ea}+\phi_d+\phi_a) \\ &+e_b\sin(\omega t+\phi_{eb})i_b\sin(\omega t+\phi_{eb}+\phi_d+\phi_b) \\ &+e_c\sin(\omega t+\phi_{ec})i_c\sin(\omega t+\phi_{ec}+\phi_d+\phi_c) \end{aligned} \tag{2}$$

Where ϕ_{en} denotes the phase angle of voltage *n* (*n=a,b,c*), and $\phi_n+\phi_d$ is the phase angle difference between voltage *n* and current *n.*

To control active and reactive powers, i_n, ϕ_n, ϕ_d should be determined properly, as follows:

A. Current Phase Angle

The instantaneous power of each phase can be stated as:

$$\begin{aligned} p_n(t) &= e_n i_n \sin(\omega t+\phi_{en})\sin(\omega t+\phi_{en}+\phi_d+\phi_n) \\ &= \frac{1}{2}(\cos(\phi_d+\phi_n)-\cos(2\omega t+2\phi_{en}+\phi_n+\phi_d)) \end{aligned} \tag{3}$$

The first term represents the average active power and the second stands for oscillatory power. In order to a phase balanced power exchange, the sum of oscillatory terms in three-phase must be zero, for this purpose the phase angle of power should be separated by $\frac{2\pi}{3}$. Therefore ϕ_n should be:

$$\begin{cases} 2\phi_{ea}+\phi_a=0 \\ 2\phi_{eb}+\phi_b=\dfrac{2\pi}{3} \\ 2\phi_{ec}+\phi_c=-\dfrac{2\pi}{3} \end{cases} \rightarrow \begin{cases} \phi_a=-2\phi_{ea} \\ \phi_b=\dfrac{2\pi}{3}-2\phi_{eb} \\ \phi_c=-\dfrac{2\pi}{3}-2\phi_{ec} \end{cases} \tag{4}$$

These relations can obviously be seen in Fig. 2.

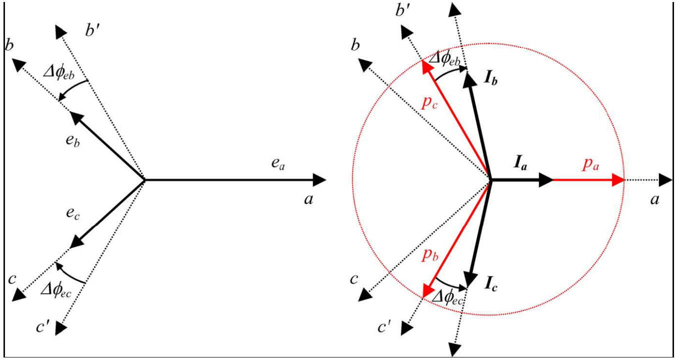

Fig. 2 Injecting current to have balanced power

When system operates in balanced condition, $\varphi_{eb}=0, \varphi_{eb}=-\frac{2\pi}{3}, \varphi_{ec}=\frac{2\pi}{3}$ that yields $\varphi_a=\varphi_b=\varphi_c=0$. This means that under balanced operation additional phase-angle difference between voltages and currents is not necessary.

B. Current amplitude

Under three-phase balanced conditions each phase provides one-third of all active power demand. It is suggested that under unbalanced condition, a higher current gets injected in those phases with higher voltage amplitude.

Let us define i_{pn} as:

$$i_{pn} = \frac{2P}{3e_n} \tag{5}$$

And also suppose that the reference current amplitude is:

$$i_n = c_n \times i_{pn} \tag{6}$$

Where C_n indicates the power variation of each phase due to imbalance.

To calculation C_n coefficients, the sum of three-phase power should be equal to power demand *P:*

$$\begin{aligned}&\frac{1}{2}[c_a \times i_{pa} e_a \cos(\varphi_{\Delta a}) + c_b \times i_{pb} e_b \cos(\varphi_{\Delta b}) \\ &+ c_c \times i_{pc} e_c \cos(\varphi_{\Delta c})] = P\end{aligned} \tag{7}$$

(7) can be simplified as:

$$c_a \cos(\varphi_{\Delta a}) + c_b \cos(\varphi_{\Delta b}) + c_c \cos(\varphi_{\Delta c}) = 3 \tag{8}$$

Furthermore, the injecting currents should never have any zero sequence components. If the current is in phasor form $I_n \measuredangle \theta_n$, the sum of currents inline with real and imaginary axis should be zero:

$$\begin{aligned}&\frac{2P}{3}[c_a \cos(\theta_a) + c_b \cos(\theta_b) + c_c \cos(\theta_c)] = 0 \\ &\frac{2P}{3}[c_a \sin(\theta_a) + c_b \sin(\theta_b) + c_c \sin(\theta_c)] = 0\end{aligned} \tag{9}$$

Using (8) and (9), the following equation should be solved in order to calculate C_n coefficients:

$$\begin{cases} c_a \cos(\varphi_{\Delta a}) + c_b \cos(\varphi_{\Delta b}) + c_c \cos(\varphi_{\Delta c}) = 3 \\ c_a \cos(\theta_a) + c_b \cos(\theta_b) + c_c \cos(\theta_c) = 0 \\ c_a \sin(\theta_a) + c_b \sin(\theta_b) + c_c \sin(\theta_c) = 0 \end{cases} \tag{10}$$

C. Average Reactive Control

So as to control the average reactive power, the desired power factor can be added to the current phase angle:

$$\varphi_{in} = \varphi_{en} + \varphi_n + \varphi_d + \varphi_{pf} \tag{12}$$

Where:

$$\varphi_{pf} = arctg(\frac{Q}{P}) \tag{13}$$

In equation (12), φ_d is added to correct average reactive power. For further explanation suppose unity power-factor operation when voltages is unbalanced (Fig. 2). The average reactive power for each phase is (*n=a,b,c*):

$$Q_n = \frac{c_n e_n i_n}{2} \sin(\varphi_n) \tag{14}$$

And total reactive power is:

$$Q_{total} = Q_a + Q_b + Q_c \tag{15}$$

It is observable that average reactive power may not be zero at pure active operation, therefore φ_d is added in (12) to guarantee that average reactive power is zero.

To calculate φ_d, the average reactive power should be zero when power factor is unity, therefore:

$$\begin{aligned}Q = &\frac{1}{2}[c_a e_a i_{pa} \sin(\varphi_a + \varphi_d) + c_b e_b i_{pb} \sin(\varphi_b + \varphi_d) \\ &+ c_c e_c i_{pc} \sin(\varphi_c + \varphi_d)] = 0\end{aligned} \tag{16}$$

With respect to (6), (16) simplified to:

$$c_a \sin(\varphi_a + \varphi_d) + c_b \sin(\varphi_b + \varphi_d) + c_c \sin(\varphi_c + \varphi_d) = 0 \tag{17}$$

Solving this equation yields:

$$\tan(\varphi_d) = -\frac{c_a \sin(\varphi_a) + c_b \sin(\varphi_b) + c_c \sin(\varphi_c)}{c_a \cos(\varphi_a) + c_b \cos(\varphi_b) + c_c \cos(\varphi_c)} \tag{18}$$

Although φ_d can be calculated from (18), it should be noticed that $\varphi_a, \varphi_b, \varphi_c$ are not significantly large so φ_d can be estimated as:

$$\varphi_d = -\frac{c_a \varphi_a + c_b \varphi_b + c_c \varphi_c}{c_a + c_b + c_c} \tag{19}$$

Computations and simulation results show that the error of this approximation is negligible, even in sever unbalanced faults.

D. proposed method steps

1) At first, φ_n is calculated from (4)

2) i_{pn} is calculated from (5)

3) The coefficients C_n are computed by solving (6)

4) φ_d is evaluated from (18) or (19).

5) The current-phase angle is determined from (12)

6) Reference current is determined as follows:

$$\begin{cases} i_a^{*} = c_a \times i_{pa} \sin(\varphi_{ia}) \\ i_b^{*} = c_b \times i_{pb} \sin(\varphi_{ib}) \\ i_c^{*} = c_c \times i_{pc} \sin(\varphi_{ic}) \end{cases} \tag{20}$$

Where superscript "*" denotes reference value.

Block diagram of the proposed method is depicted in Fig. 3.

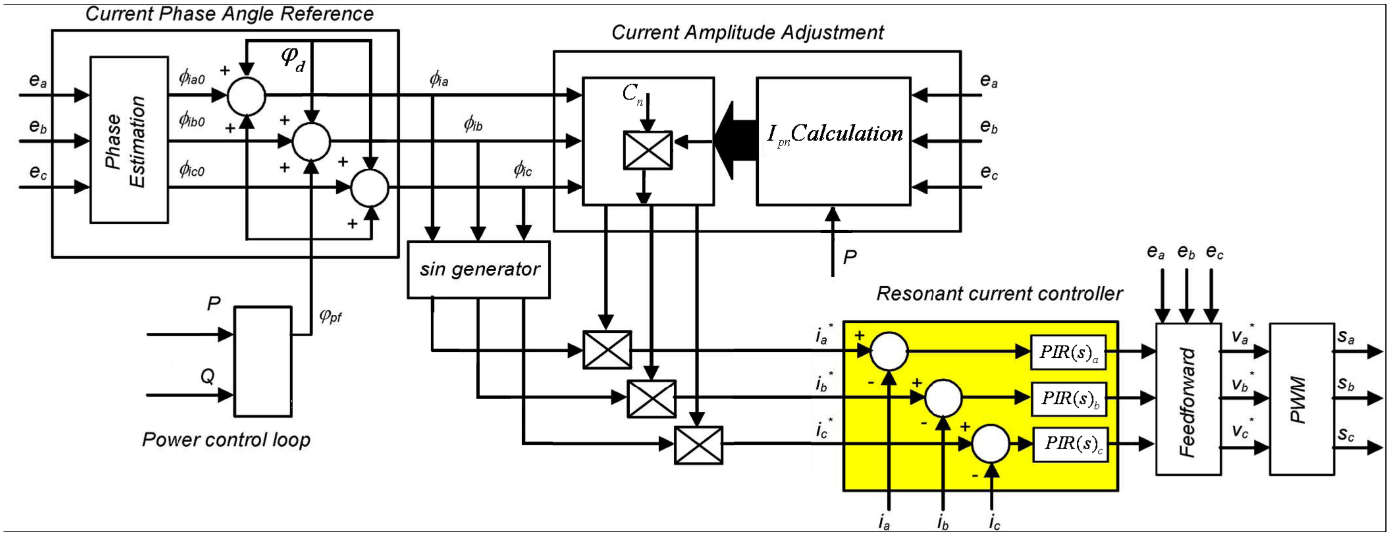

Fig. 3.Block diagram of controller

IV. CONTOLLER

A. synchronization

Proper synchronization with the utility voltages is one of the most aspects to consider in the control of power converters. Most of synchronization methods proposed in literature are based on conventional PLLs which have poor performance under unbalanced voltages [8].

[7] Proposed DFT[1] method is used to extract amplitude and angle of phase-voltages. Although, DFT method is fast and has an exact performance but it is very sensitive to frequency deviation and needs additional criteria to adopt frequency. Furthermore, this method needs relatively heavy computations.

To avoid these problems an EPLL-based synchronization method introduced in [8] has been used. This method has a very good performance in unbalanced and distorted conditions and is suitable for VSC synchronization. The discrete-time recursive equations of EPLL are:

$$\begin{cases} A[n+1] = A[n] + \mu_1 e[n]\sin(\varphi[n]) \\ \varphi[n+1] = \varphi[n] + T_s\omega[n] + \mu_2 e[n]\cos(\varphi[n]) \\ \omega[n+1] = \omega[n] + \mu_2 e[n]\cos(\varphi[n]) \\ e[n+1] = u[n+1] - A[n+1]\sin(\varphi[n+1]) \end{cases} \tag{21}$$

Where A, φ, ω are amplitude, phase-angle and frequency (rad/sec) of voltage, respectively.

The EPLL parameters have been chosen in such a way that the natural frequency equals to $2\pi \times 30\,\text{Hz}$. With this bandwidth, the high order switching component has not any effect on the EPLL performance.

B. Current controller

Using PI controller in the synchronous reference frame (dq) is a common way to nullify the steady state error. But in the stationary and three-phase (*abc*) reference frame, PI controller cannot remove the steady state error. Also limited bandwidth causes the controller to exhibit a poor performance. For this reason, this paper used resonant controller in the form of [7]:

$$PIR = k_p + \frac{2k_i s}{s^2 + \omega^2} \tag{22}$$

It is obvious that this controller has infinitive gain at $s = j\omega$ so it can guarantee the zero steady state error.

C. Frequency adoption

Any frequency deviation from the nominal value of 50/60 Hz, substantially degrade the performance of the controller which operates based on assumption of constant frequency. As stated in the previous section, the controller needs exact value of $\omega = 2\pi f$ to have a good performance.

In order to determine the instantaneous ω, this paper proposed that ω is calculated as:

$$\omega = \frac{\omega_a + \omega_b + \omega_c}{3} \tag{23}$$

Where ω_n is the frequency (rad/sec) of phase *n* (*n=a,b,c*) which is determined by the EPLL of the same phase.

Fig. 4 shows the actual and estimated ω, when the frequency begins to change at t=2.5 sec until t=3 sec in the rate of 2 Hz/sec.

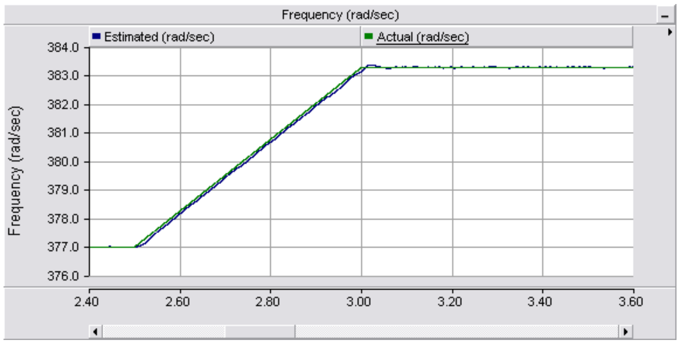

Fig. 4. Actual and estimated frequencies (rad/sec) diagram

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[1] Discrete Fourier Transform

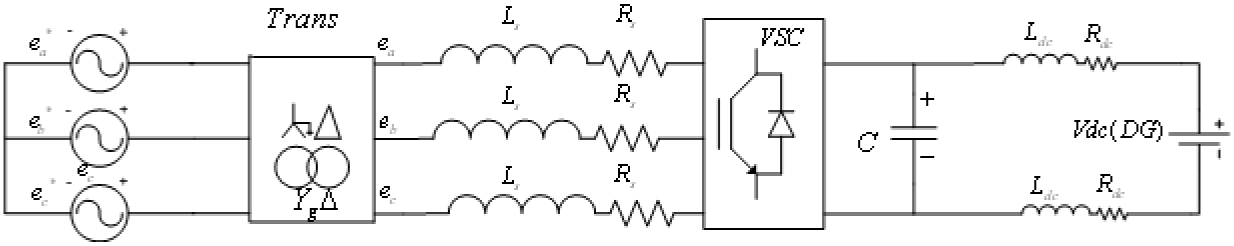

Fig. 5. Test model was implemented at PSCAD/EMTDC

V. SIMULATION RESULTS

The suggested method has been implemented in test system of Fig. 5 which proposed in [7] .The simulation has been done in PSCAD/EMTDC environment.

It is assumed that the system operates normally. at t=2 sec, one "D" type sag is applied to converter which demonstrates that a line to line fault happens in the system [10], furthermore frequency begins to change at t=2.5 sec until t=3 sec in the rate of 2 Hz/sec. then fault is cleared at t=3.2 sec.

Results are presented in Fig. 5 (instantaneous active power), Fig. 6 (instantaneous reactive power) and Fig. 8 (DC bus voltage). It can clearly be seen that the active power delivered to grid is constant without any oscillation before and after the fault. The capacitor dc voltage has a low alternation which is due to filter (R_f, L_f) effect [11].

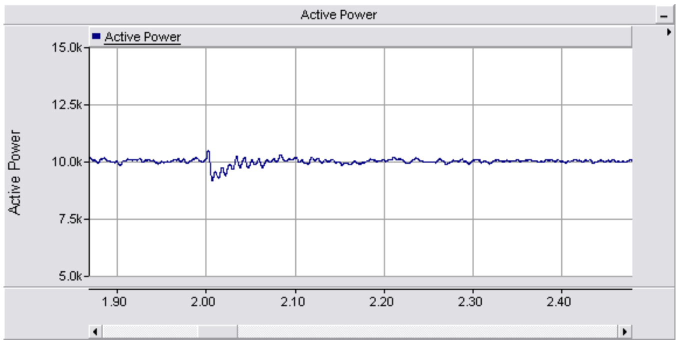

Fig. 6. Instantaneous active power (*pf=1*)

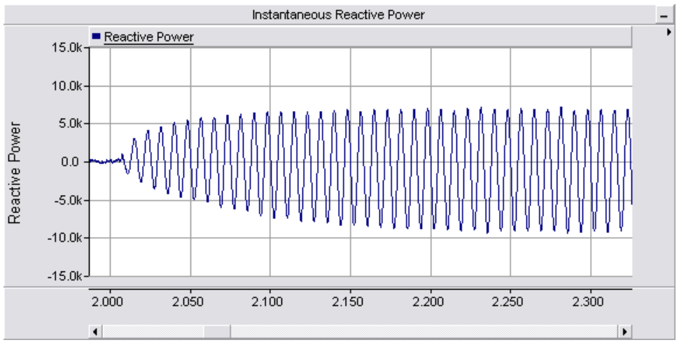

Fig. 7. Instantaneous reactive active power (*pf=1*)

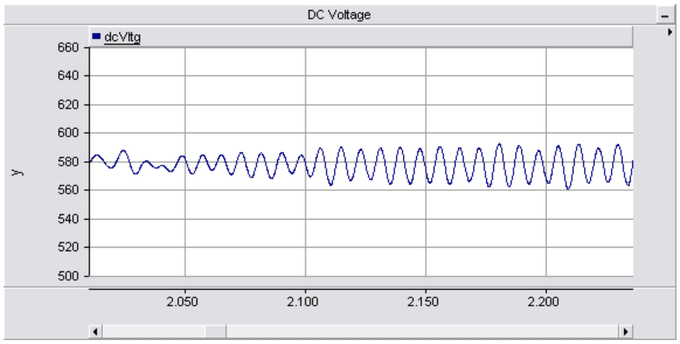

Fig. 8. DC bus voltage

Fig. 7 shows that the instantaneous reactive power is very oscillatory with a zero average. This substance is discussed at comment after (1) that the reactive power should be uncontrollably oscillatory. The important note is that the average reactive power is zero because the desired power factor is unity. Any other average reactive power can be set by correct calculation of φ_d, φ_{pf} (see section III part *D*),

For more clarification the previous example will simulated again with *pf=.707.* In this power factor operation the active and average reactive powers should be equal.

This matter obviously can be seen in Fig. 9 and Fig. 10.

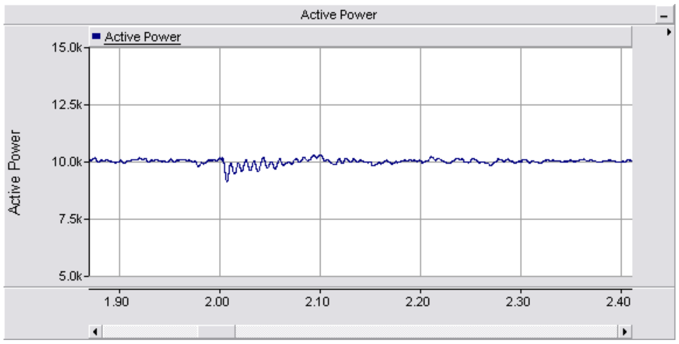

Fig. 9. Instantaneous active power (*pf=.707*)

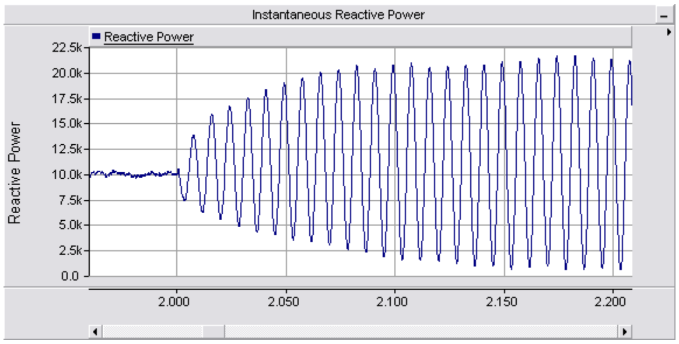

Fig. 10. Instantaneous reactive power (*pf=.707*)

Fig. 11 shows the instantaneous active power delivered to grid during the fault, when frequency changes. Fig. 12 shows the actual and estimated frequency of the grid. It can be shown that EPLL can adopt frequency carefully, and power delivered to the grid is truly constant and equals to power demand.

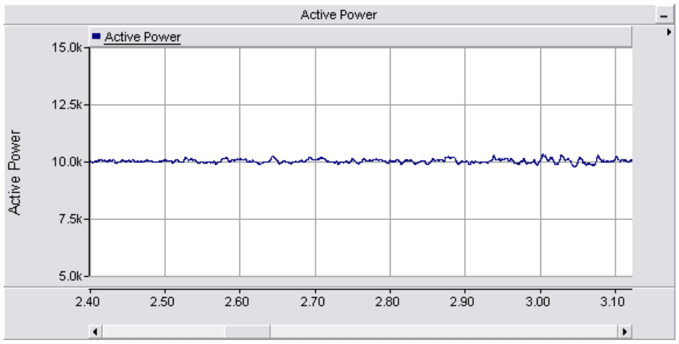

Fig.11. Instantaneous active power diagram under frequency deviation

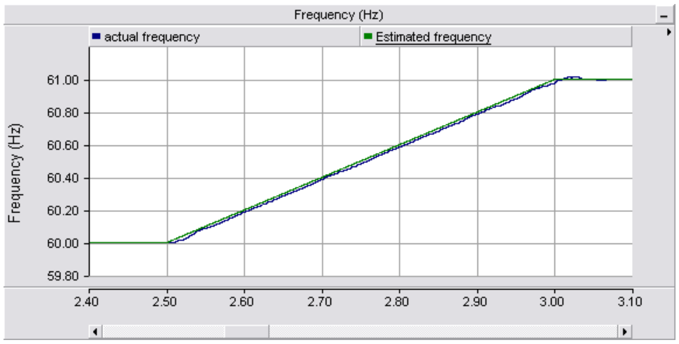

Fig. 12. Actual and estimated frequencies (Hz).

VI. CONCLUSION

This paper proposed a new method to control power exchanging with independent control for active and reactive powers. This method has been directly implemented in three-phase (*abc*) reference frame by using resonant controller. EPLL is used to extract amplitude and angle of phase-voltages. Using EPLL can also provide frequency adaption which is very necessary for resonant controller.

The simulation results show that this method has a good and fast performance and is suitable for faulty and time-varying frequency grids.

REFERENCES

[1] Timbus, A.V. Rodriguez, P. Teodorescu, R. Liserre, M. Blaabjerg, F. , "Control Strategies for Distributed Power Generation Systems Operating on Faulty Grid Industrial Electronics, 2006 IEEE International Symposium on Montreal, Que, Volume , Issue , July 2006 p. 1601-1607

[2] F. Blaabjerg, Z. Chen, and S. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," IEEE Trans. on Power Electronics, vol. 19, no. 5, pp. 1184-1194, 2004.

[3] R. Strzelecki, G. Benysek, *Power electronics in smart electrical energy networks*, *1rd ed* , Berlin:springer, 2008.

[4] C. H. Ng, L .Ran, J. Bumby, "Unbalanced-Grid-Fault Ride-Through Control for a Win Turbine Inverter,*" IEEE Trans on Industrial Applications, Vol. 44, No.3, May/June 2008.*

[5] H. S. Song and K. Nam, "Dual current control scheme for PWM converter under unbalanced input voltage conditions," *IEEE Trans. Ind. Electron.*, vol. 46, no. 5, pp. 953–959, Oct. 1999.

[6] Rodriguez, P.; Timbus, A. V.; Teodorescu, R.; Liserre, M.; Blaagjerg, F.,Flexible Active Power Control of Distributed Generation Systems During Grid Faults" *IEEE Trans. Ind. Electron.,* vol. 54, no. 5, pp. 1398–1409, Oct. 2007.

[7] I.Etxebrria- otadui, U.Viscarret, M.Caballero, A.Rufer, S.Bacha, "New Optimized PWM VSC Control Structures and Strategies Under unbalanced Voltage Transients*," IEEE Trans on Industrial Electronics, Vol. 54, No.5, October 2007.*

[8] P. Rodríguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, "Decoupled double synchronous reference frame PLL for power converters control," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 584–592, Mar. 2007.

[9] M. Karimi-Ghartemani and M. R. Iravani, "A method for synchronization of power electronic converters in polluted and variable- frequency environments," IEEE Trans. Power Syst., vol. 19, no. 3, pp. 1263–1270, Aug. 2004.

[10] A. Sannino, M. H. J. Bollen, and J. Svensson, "Voltage tolerance testing of three-phase voltage source converters," *IEEE Trans. Power el.*, vol. 20, no. 2, pp. 1633–1639, Apr. 2005.

[11] A.YAzdani, R.Iravani, "A Unified Dynamic Model and Control for the Voltage-Sourced Converter under Unbalanced Grid Condition", *IEEE Trans on. Power Del,* Vol. 21, No 3, July 2006