Unsymmetrical Fault Correction for Sensitive Loads Utilizing a Current Regulated Inverter

Syed Sabir Hussain Bukhari, Byung-il Kwon
Electronic Systems Engineering
Hanyang University
Ansan-si, Gyeonggi-do, Korea
sabir@hanyang.ac.kr, bikwon@hanyang.ac.kr

Thomas A. Lipo
Electrical Engineering
University of Wisconsin-Madison
Madison, WI 53706, USA
lipo@engr.wisc.edu

***Abstract*—Many industrial applications involve loads which are very sensitive to electrical disturbances in the supply. These instances involve both various types of voltage unbalance as well as more series disturbances such as symmetrical and asymmetrical faults. This paper proposes a voltage unbalance and an unsymmetrical fault correction technique for a three phase load utilizing an industry-standard current regulated voltage source inverter by connecting it in parallel to the associated three phase transformer. The inverter regulates the current for the load and never allows the current to exceed to a prescribed value under any type of unsymmetrical condition.**

I. INTRODUCTION

Fault management is a matter of great interest because they can cause a number of serious problems in the electrical transmission and distribution systems as well as for sensitive loads. Typical examples of industrial applications which demand a tightly regulated power supply include semiconductor processing, EMC testing, EMI testing and magnetic field generation. The conventional means to deal with this problem is by providing a custom power supply containing dedicated power electronic components [1]-[2]. While this solution is effective, it is costly and used only in a few applications. In this paper a low cost solution to this problem is proposed in which a conventional cost-minimized rectifier/inverter normally utilized as the electrical supply for a variable frequency ac motor load is used to regulate power by placing it in parallel with the transformer associated with the sensitive load.

In general, faults can either be symmetrical or unsymmetrical. Symmetrical faults constituting a three phase short circuit lead to severe voltage sags at the primary side of the transformer. Fortunately they are very rare in the power systems constituting only about 1% of occurrences. Unsymmetrical faults cause voltage sags with higher magnitudes (voltage sag magnitude is defined here as the magnitude of the remaining voltage at the bus). However they are much more common in the power systems. It is well known that the probability of a single line-to-ground (L-G) fault is 80%, double line-to-ground fault (DL-G) is 17%, line-to-line fault (L-L) is 2% while the three phase fault is only about 1% [3]. Since a three phase fault involves complete interruption of the power flow from the utility, this type of condition can only be effectively dealt with by utilizing an expensive UPS having a separate battery or diesel generator power supply.

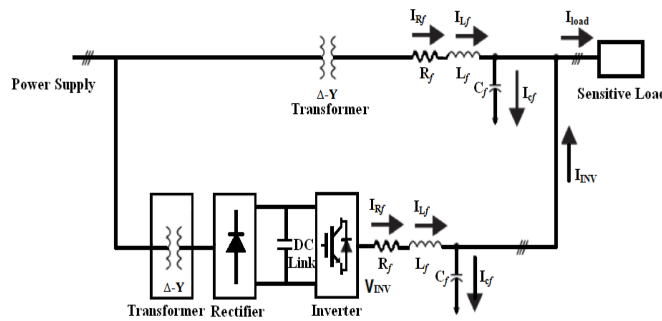

Figure 1. Proposed unsymmetrical fault correction technique for a sensitive three phase load.

A much less expensive solution is possible if protection against any of the fault conditions other than a three phase fault is considered adequate. The proposed circuit configuration is shown in Figure 1. In contrast to a UPS system the inverter in this case is always physically connected to the consumer bus and can thus act almost instantly to a disturbance in the power source. The sole responsibility of the inverter is to keep three phase currents constant and balanced on the secondary side of the transformer. If the power system experiences any type of unsymmetrical fault or suffers from a source voltage unbalance, the power is then balanced by a current regulated voltage source inverter using high bandwidth control technology originally developed for ac motor drives [4]-[5]. Although the asymmetrical fault causes a disturbance to the dc voltage link of the power converter as well as the load, it is shown that this effect can be effectively eliminated by tight regulation of the inverter current. Thus, the possibility of the damage of the system equipment, consumer's critical loads and the interruption of service to a consumer can be almost eliminated during 99% of the fault conditions.

II. OPERATING PRINCIPLE

The proposed voltage unbalance and fault correction control technique of Figure. 1 utilizes a current controller implemented in the synchronously rotating reference frame. In this case the inverter effectively acts as a fast acting current source. To perform the proposed operation, a current control scheme as shown in Figure. 2 have been used.

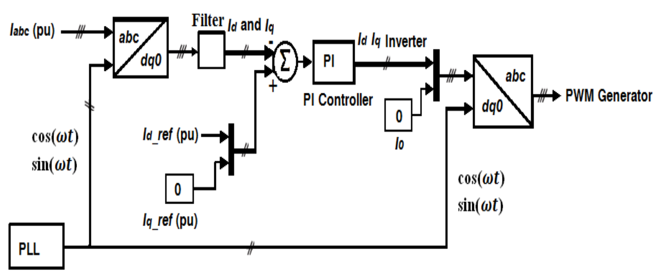

Figure 2. Current controller for the inverter in *dq0* frame of reference.

To control the current for the load, the inverter uses the measured three phase currents I_{abc} (pu) as the feedback currents for the controller which are first transformed from the *abc* frame of reference to *dq0* frame of reference through Park's Transformation by using following equations:

$$I_d = 2/3\ [I_a \sin(\omega t) + I_b \sin(\omega t\text{-}2\pi/3) + I_c \sin(\omega t+2\pi/3)] \quad (1)$$

$$I_q = 2/3\ [I_a \cos(\omega t) + I_b \cos(\omega t\text{-}2\pi/3) + I_c \cos(\omega t+2\pi/3)] \quad (2)$$

$$I_0 = 1/3\ [I_a + I_b + I_c] \quad (3)$$

After the transformation, the three output currents I_d, I_q and I_0 are then filtered to give I_d and I_q currents leaving behind I_0 for the comparison with the reference currents I_d_ref (pu) *and* I_q_ref (pu). The comparison of the selected I_d and I_q with the reference I_d and I_q currents results in error signals which are fed to the PI controller. The output of the PI controller after combining with I_0 is used as the control signals to the PWM generator for the required commutation of the inverter. Before the control signals are sent to the PWM generator they are converted back to the *abc* frame of reference by using following inverse Park's Transformation equations:

$$I_a = I_d \sin(\omega t) + I_q \cos(\omega t) + I_0 \quad (4)$$

$$I_b = I_d \sin(\omega t\text{-}2\pi/3) + I_q \cos(\omega t\text{-}2\pi/3) + I_0 \quad (5)$$

$$I_c = I_d \sin(\omega t+2\pi/3) + I_q \cos(\omega t+2\pi/3) + I_0 \quad (6)$$

where "ω" is the rotation speed (rad/sec) of the rotation frame. A phase-locked loop (PLL) is used for the input signals of sin(ωt) and cos(ωt) during transformations.

For the current regulator parameters of this controller, the values for the proportional gain (K_p) and the integral gain (K_i) are 10 and 1000 respectively.

III. RESULTS AND DISCUSSION

To validate the proposed unsymmetrical fault correction technique for the sensitive loads, a system as shown in Figure. 1 has been used for the simulations. The values are consistent with a relatively small laboratory setup presently undergoing tests. The simulations have been performed through MATLAB/SIMULINK and the system parameters are given as follows:

Supply/Grid: 220V, 60 Hz and 220/410 V_{rms} transformer is rated at 500 VA with the delta/wye connection.
Transformer: A 220/220 V_{rms} (l-l) transformer rated at 1 kVA with delta/wye connection.
Load: A passive load of 1 kVA, operating at 220 V_{rms} is considered to be the consumer's demand.
Inverter: A conventional three-pole PWM current regulated voltage source inverter with hard switching at 5 kHz.
Filter: Two RLC output filters are used at the inverter and the transformer output respectively. The filter resistance (R_f) is 1 ohm, inductance (L_f) is 20 mH and the capacitance (C_f) is 10µF each. The dc-bus voltage is 560 V.

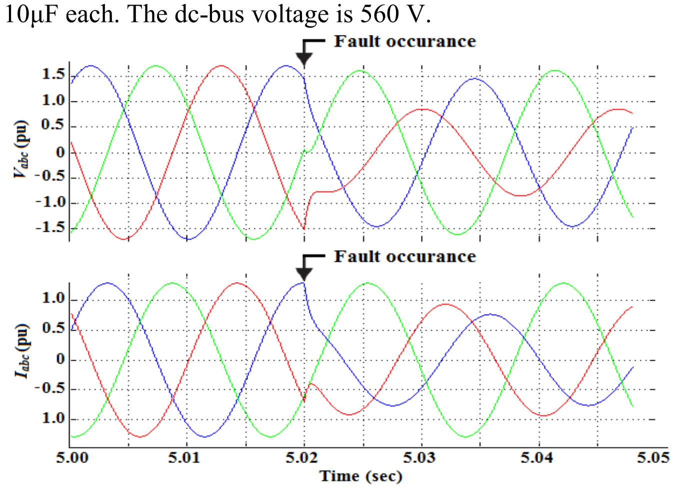

Figure 3. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a single line-to-ground (L-G) fault without the proposed unsymmetrical fault correction technique.

The simulation results for the three phase load currents I_{abc} (pu) and voltages V_{abc} (pu) without the proposed unsymmetrical fault correction technique are shown in Figures 3, 4 and 5. Figure 3 shows the behaviour of load during a single line-to-ground (L-G) fault whereas Figures 4 and 5 show the simulation results for the same load during a line-to-line (L-L) and double line-to-ground (DL-G) faults respectively.

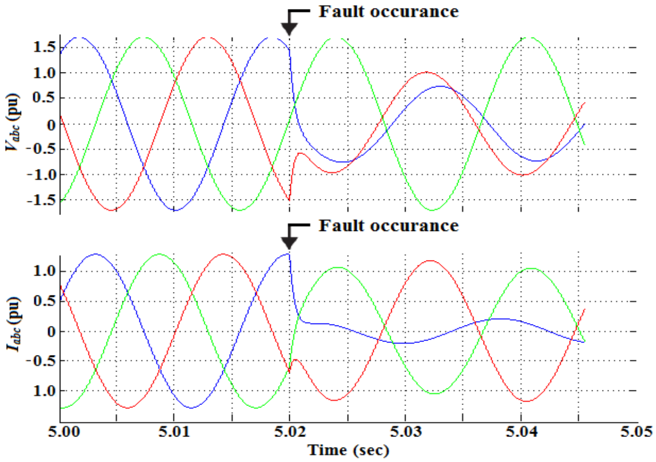

Figure 4. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a line-to-line (L-L) fault without the proposed unsymmetrical fault correction technique.

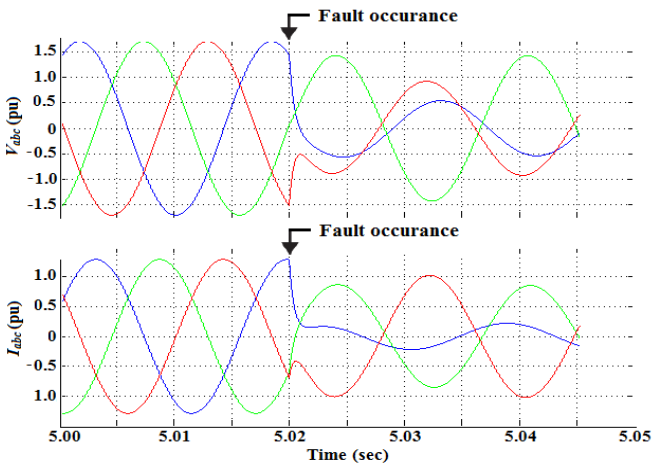

Figure 5. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a double line-to-ground (DL-G) fault without the proposed unsymmetrical fault correction technique.

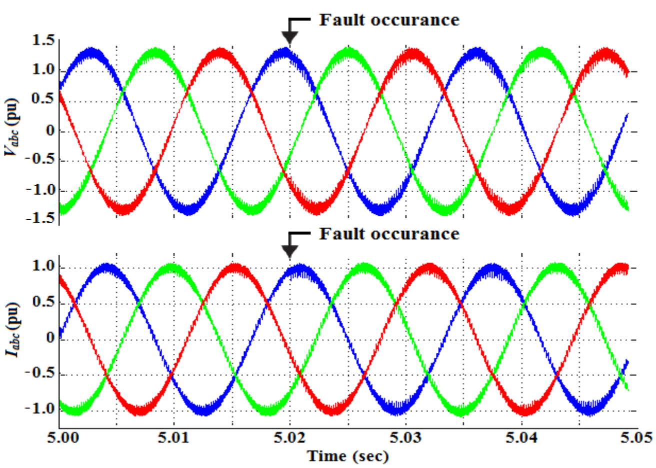

Figure 6. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a single line-to-ground (L-G) fault with the proposed unsymmetrical fault correction technique.

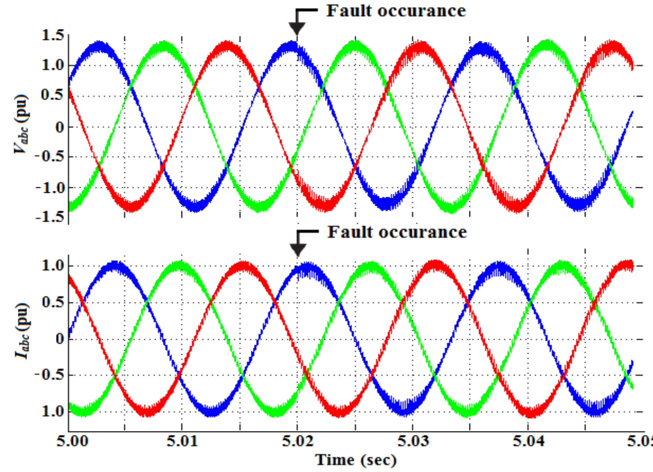

Figure 7. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a line-to-line (L-L) fault with the proposed unsymmetrical fault correction technique.

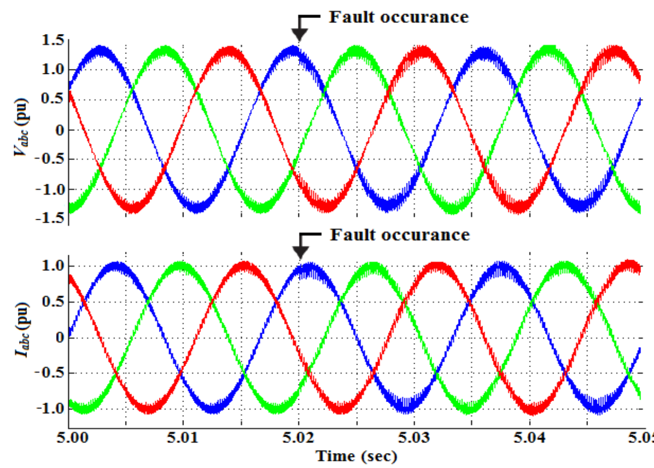

Figure 8. Simulation results for the three phase load currents (I_{abc}) and voltages (V_{abc}) during a double line-to-ground (DL-G) fault with the proposed unsymmetrical fault correction technique.

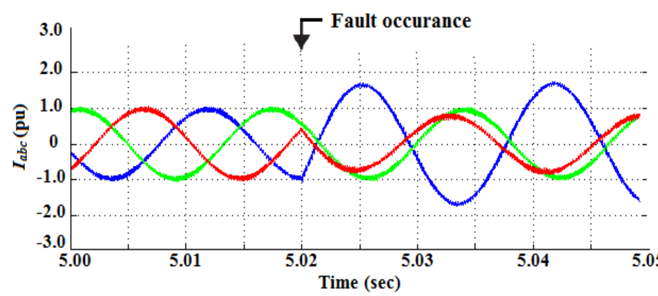

Figure 9. Simulation results for the three phase inverter currents (I_{abc}) during a single line-to-ground (L-G) fault with the proposed unsymmetrical fault correction technique.

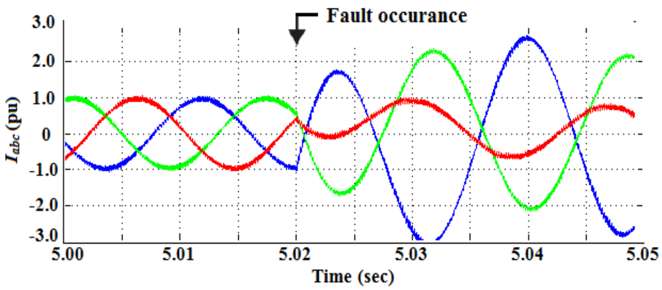

Figure 10. Simulation results for the three phase inverter currents (I_{abc}) during a single line-to-line (L-L) fault with the proposed unsymmetrical fault correction technique.

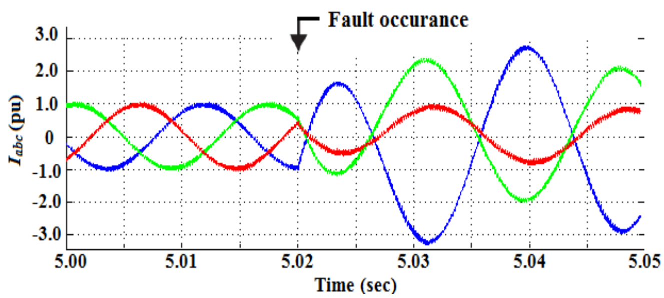

Figure 11. Simulation results for the three phase inverter currents (I_{abc}) during a double line-to-ground (DL-G) fault with the proposed unsymmetrical fault correction technique

Figures 6, 7 and 8 show the simulation results for the three phase load currents I_{abc} (pu) and voltages V_{abc} (pu) and Figures 9, 10 and 11 show the simulation results for the three phase inverter currents I_{abc} (pu) with the proposed unsymmetrical fault correction technique when power system experiences an unsymmetrical fault i.e. single line-to-ground (L-G) fault, line-to-line (L-L) fault and double line-to-ground (DL-L) fault. These asymmetrical faults cause distrubance not only for the sensitive load connected to the grid but also for the dc link voltage of the power converter. Figures 12, 13 and 14 show the change in the dc link voltage during such faults. For the performed simulation results, the fault occurance time (t_{fault}) is 5.02 sec. The impedances of the transformers used for the simulations are given in Table 1.

TABLE 1
IMPEDANCES OF TRANSFORMERS

R_1	L_{l1}	R_2	L_{l2}
0.002(p.u)	0.079(p.u)	0.0022(p.u)	0.0891(p.u)

From the performed simulation results given it can be seen that the load currents with the proposed fault correction technique are balanced and constant if the power supply goes through any of the mentioned unsymmetrical faults.

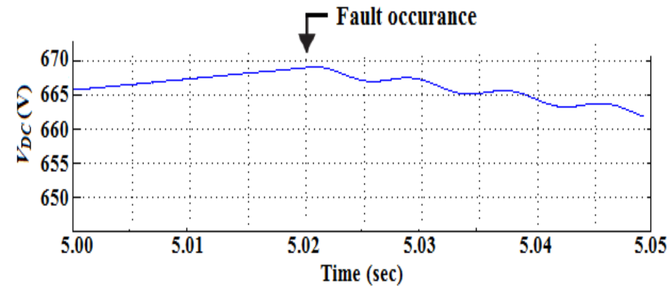

Figure 12. DC link voltage V_{DC} (V) when the grid experiences a single line-to-ground (L-G) fault.

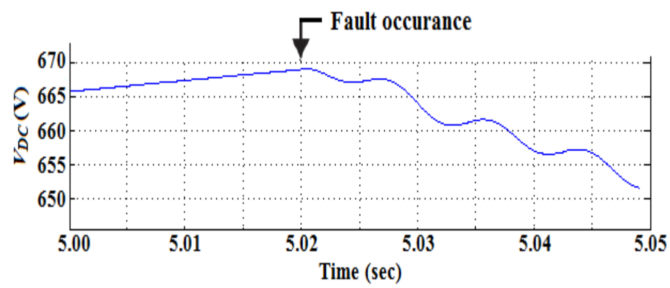

Figure 13. DC link voltage V_{DC} (V) when the grid experiences a single line-to-line (L-L) fault.

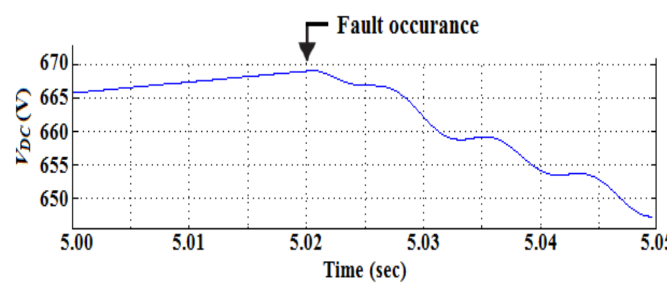

Figure 14. DC link voltage V_{DC} (V) when the grid experiences a double line-to-ground (DL-G) fault.

IV. CONCLUSION

A solution to the problem associated with unsymmetrical faults and unbalances has been discussed in this paper. This paper proposes using a standard current regulated voltage source inverter connected in parallel to the three phase transformer. A fast responding control system enables the inverter to regulate the current for the sensitive load under all unsymmetrical fault conditions.

The proposed technique avoids interruption of the power supply under fault conditions and provides protection to critical loads for 99% of normally encountered fault conditions. Furthermore, since the system requires only a typical standard inverter, the proposed technique could prove to be an economic solution for load sensitive applications which do not warrant the use of a custom power supply.

REFERENCES

[1] Reed, G.F. , Croasdaile, T.R. , Paserba, J.J. , Williams, R.M., Takeda, M. , Jochi, S. , Morishima, N. , Aritsuka, T., Hamasaki,Y. , Yonehata, Y. , Amakasu, S. ,Takamiya, K. , "Applications of voltage source inverter (VSI) based technology for FACTS and custom power installations," *Power System Technology, Proceedings PowerCon 2000. International Conference on*, Publication Year: 2000 , Page(s): 381 – 386, vol. 1.

[2] Stump, M.D. , Keane, G.J. , Leong, F.K.S.,"The role of custom power products in enhancing power quality at industrial facilities," *Energy Management and Power Delivery, 1998. Proceedings of EMPD '98. 1998 International Conference on,* Publication Year: 1998 , Page(s): 507 - 517 vol. 2.

[3] J. Beiza, S. H. Hosseinian and B. Vahidi, "Fault Type Estimation in Power Systems," *Iranian Journal of Electrical and Electronics Engineering*, Vol. 5, No. 3, Sep. 2009.

[4] A. Veltman, D.W.J. Pulle and R. DeDoncker, "Advanced electrical drives," (book) *Springer Verlag*, Heidelberg, 2011.

[5] Syed Sabir Hussain Bukhari, Thomas A. Lipo and Byung-il Kwon, "An Inrush Current Reduction Technique for the Line-Interactive Uninterruptible Power Supply System," *Annual Conference of Industrial Electronics Society, 2013*, *Proceedings of . IECON'13*, pp. 428-432.