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A Generalized Control Method for Input-Output Harmonic Elimination for the PWM Boost Rectifier Under Simultaneous Unbalanced Input Voltages and Input Impedances

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A Generalized Control Method for Input-Output Harmonic Elimination for the PWM Boost Rectifier Under Simultaneous Unbalanced Input Voltages and Input Impedances

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Abstract— **Under severe fault conditions in the distribution system, not only input voltages, but also input impedances must be considered as unbalanced. This paper presents a new control method for input-output harmonic elimination of the PWM-Boost Type Rectifier under conditions of both unbalanced input voltages and unbalanced input impedances. The range of unbalance in both input voltages and input impedances, for which the proposed method is valid, is analyzed in detail.**

An analytical approach for complete harmonic elimination shows that PWM Boost Type Rectifier can operate at unity power factor under extreme unbalanced operating conditions resulting in a smooth (constant) power flow from ac to dc side. Based on the analyses in the open loop configuration, a feed-forward control method is proposed.

Elimination of harmonics at ac and dc side of the converter affects the cost of dc link capacitor and ac side filter. The proposed method is very useful when PWM Boost Type Rectifier is subject to extreme unbalance due to severe fault conditions in the power system. In addition, by using the proposed method, the PWM Boost Type Rectifier can be operated from the single-phase supply in cases where three-phase source is not available.

Simulation results show excellent response and stable operation of the PWM Boost Type Rectifier under the proposed control algorithm.

I. INTRODUCTION

The PWM Boost Type Converter has been increasingly employed in recent years [3], [7]. It offers advantages over traditionally used phase controlled rectifiers in AC/DC/AC converters for variable control drives because of its capability for nearly instantaneous reversal of power flow, power factor management and reduction of input harmonic distortion. Although numerous papers have been written about the PWM Boost Type Rectifier, its operation under unbalanced input supply voltages and impedances has not been analyzed in detail. Such an unbalance may occur frequently especially in weak systems. Nonuniformly distributed single phase loads, faults or unsymmetrical transformer windings could cause unbalance in the three-phase supply both in magnitude and in phase. Regardless of the cause, unbalanced input voltages have a severe impact on the performance of the PWM Boost Type Rectifier. An unbalanced input supply results in the appearance of large low order harmonics at the rectifier output as well as low order harmonics in the input currents that pollute the utility [2]. Such harmonic pollution has been of the growing concern in recent years. In addition to harmonic pollution at the ac side of the converter, the ripple at the DC link is a known cause of interaction between current regulators which could even cause system instability [8]. The problem increases as the number of converters at the link increases. Attempts have been made to reduce harmonics at the input and the output of the PWM Boost Type Rectifier under unbalanced operating conditions [5]. However, harmonics were reduced but not eliminated. Enjeti and Choudhury [6] proposed a method of input harmonic elimination of the buck ac to dc converter. Recently, Stankovic and Lipo [1] proposed a new control method for complete input-output harmonic elimination of the PWM Boost Type Rectifier under unbalanced operating conditions. However, this method suffers from two disadvantages: the power factor can not be adjusted and it can not operate under extreme unbalanced operating conditions. In other words, the issue of complete harmonic elimination with adjustable power factor under extreme unbalanced operating conditions with unbalanced impedances has never been addressed.

This paper proposes a completely new strategy for input output harmonic elimination of the PWM Boost Type Rectifier under extreme unbalanced operating conditions. The power factor can be adjusted in addition to the harmonic elimination. Based on the measurements of the input voltage and impedance unbalance, both magnitudes as well as phase angles of three input currents are adjusted. In spite of the level of unbalance in input voltages and input impedances, high quality of input currents and output dc voltage are obtained. The important result that follows is the possibility of operation of the three phase pwm boost type rectifier from a single phase supply with essentially no input or output harmonics.

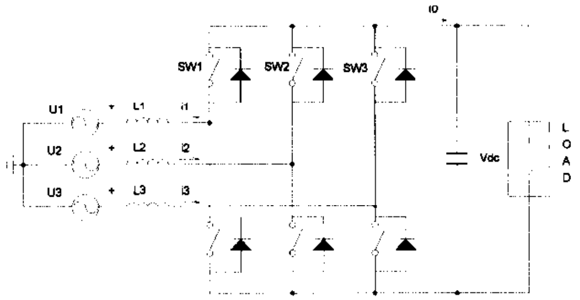

Fig. 1. The PWM Boost Type Rectifier Under Unbalanced Input Voltages and Unbalanced Input Impedances

Theoretical and simulation results show excellent agreement.

II. THEORETICAL APPROACH

The circuit in Figure 1 is analyzed under the following assumptions:

1. The input voltages are unbalanced.
2. The input impedances are unbalanced.
3. The converter is lossless

Harmonic elimination can be achieved by generating unbalanced reference commands for three input currents under unbalanced input voltages and unbalanced input impedances.

Derivation:

From the circuit shown on Figure 1 it follows that,

$$U_1 = z_1 I_1 + V_{s1} \tag{1}$$

$$U_2 = z_2 I_2 + V_{s2} \tag{2}$$

$$U_3 = z_3 I_3 + V_{s3} \tag{3}$$

$$I_1 = -I_2 - I_3 \tag{4}$$

$$S^* = U_1^* I_1 + U_2^* I_1 + U_3^* I_3 \tag{5}$$

$$SW_1 I_1 + SW_2 I_2 + SW_3 I_3 = 0 \tag{6}$$

where U_1, U_2, U_3, I_1, I_2, I_3, z_1, z_2, z_3,V_{s1},V_{s2},V_{s3}, S, SW_1, SW_2 and SW_3 are input voltages, input currents, input impedances, synthesized voltages at the input of the rectifier, apparent power and switching functions, respectively, represented as phasors.

Equation (6) represents the condition for the second harmonic elimination. Synthesized voltages can be expressed as,

$$V_{s1} = SW_1 \frac{V_{dc}}{2\sqrt{2}} \tag{7}$$

$$V_{s2} = SW_2 \frac{V_{dc}}{2\sqrt{2}} \tag{8}$$

$$V_{s3} = SW_3 \frac{V_{dc}}{2\sqrt{2}} \tag{9}$$

where V_{dc} is output DC voltage.

By substituting equations (7), (8) and (9) into (1), (2) and (3) the following set of equations is obtained,

$$U_1 = z_1 I_1 + SW_1 \frac{V_{dc}}{2\sqrt{2}} \tag{10}$$

$$U_2 = z_2 I_2 + SW_2 \frac{V_{dc}}{2\sqrt{2}} \tag{11}$$

$$U_3 = z_3 I_3 + SW_3 \frac{V_{dc}}{2\sqrt{2}} \tag{12}$$

$$I_1 = -I_2 - I_3 \tag{13}$$

$$S^* = U_1^* I_1 + U_2^* I_1 + U_3^* I_3 \tag{14}$$

$$SW_1 I_1 + SW_2 I_2 + SW_3 I_3 = 0 \tag{15}$$

For given input power S, , input voltages, U_1, U_2, U_3 and input impedances z_1,z_2 and z_3, input currents I_1, I_2, and I_3, can be obtained from the above set of equations. By multiplying equations (10), (11) and (12) by I_1, I_2, and I_3, respectively, and adding them up the following equation is obtained ,

$$U_1 I_1 + U_2 I_2 + U_3 I_3 =$$

$$z_1 I_1^2 + z_2 I_2^2 + z_3 I_3^2 + \frac{V_{dc}}{2\sqrt{2}} (SW_1 I_1 + SW_2 I_2 + SW_3 I_3) \tag{16}$$

By substituting equation (15) into (16) the following equation is obtained,

$$U_1 I_1 + U_2 I_2 + U_3 I_3 = z_1 I_1^2 + z_2 I_2^2 + z_3 I_3^2 \tag{17}$$

The set of six equations with six unknowns, (10) to (15), reduces to three equations with three unknowns and are given by,

$$I_1 = -I_2 - I_3 \tag{18}$$

$$S^* = U_1^* I_1 + U_2^* I_1 + U_3^* I_3 \tag{19}$$

Equations (17), (18) and (19) represent a set of three equations with three unknowns.

By substituting equation (18) into equations (17) and (19), the following set of equations is obtained and given by,

$$U_1(-I_2-I_3)+U_2I_2+U_3I_3 = z_1(-I_2-I_3)^2+z_2I_2^2+z_3I_3^2 \tag{20}$$

$$S^* = -U_1^*I_2 - U_1^*I_3 + U_2^*I_1 + U_3^*I_3 \tag{21}$$

Equation (20) can be simplified as,

$$I_2(U_2-U_1)+I_3(U_3-U_1) = (z_1+z_2)I_2^2+(z_1+z_3)I_3^2+2z_1I_2I_3 \tag{22}$$

From equation (21) current, , can be expressed as,

$$I_2 = \frac{S^* - I_3(U_3^* - U_1^*)}{U_2^* - U_1^*} \tag{23}$$

Finally by substituting equation (23) into equation (22),

$$\frac{S^* - I_3(U_3^* - U_1^*)}{U_2^* - U_1^*}(U_2 - U_1) + I_3(U_3 - U_1) =$$

$$(z_1 + z_2)\frac{S^{*2} - 2S^*I_3(U_3^* - U_1^*) + I_3^2(U_3^* - U_1^*)^2}{(U_2^* - U_1^*)^2} +$$

$$(z_1 + z_2)I_3^2 + 2z_1\frac{S^* - I_3(U_3^* - U_1^*)}{U_2^* - U_1^*} \tag{24}$$

$$\left[\frac{2z_1(U_3^* - U_1^*)}{U_2^* - U_1^*} - \frac{(z_1 + z_2)(U_3^* - U_1^*)^2}{(U_2^* - U_1^*)^2} - (z_1 + z_3)\right] I_3^2 +$$

$$\left[(U_3 - U_1) - \frac{(U_3^* - U_1^*)(U_2 - U_1)}{U_2^* - U_1^*}\right] I_3 -$$

$$\frac{2z_1S^*}{U_2^* - U_1^*}I_3 + \tag{25}$$

$$\frac{2S^*(z_1 + z_2)(U_3^* - U_1^*)^2}{(U_2^* - U_1^*)^2}I_3 +$$

$$\frac{S^*(U_2 - U_1)}{U_2^* - U_1^*} - \frac{(z_1 + z_2)S^{*2}}{(U_2^* - U_1^*)^2} = 0 \tag{26}$$

Currents $I_1$and I_2 can be obtained from equations (18) and (23).

Equations (18), (23) and (25) represent the steady state solution for input currents under both unbalanced input voltages and unbalanced input impedances. An analytical solution represented by equation (25) always exists unless all the coefficients of the quadratic equations are equal to zero.

A. *Critical Evaluation*

The analytical solution that has been obtained is general. In particular, the PWM Boost Type Rectifier can operate with unity power factor and still maintain DC voltage at the output. The only constraint that exists, as far as the level of unbalance is concerned, is governed by constraints of the operation of the PWM bridge itself.

The proposed generalized method for input-output harmonic elimination is valid if and only if $U_i, z_i \neq 0$,where i =1,2,3. In other words the solution exists for all levels of unbalance in input voltages and impedances, except for cases where both voltage and impedance in the same phase are equal to zero. Therefore, the maximum level of input voltage imbalance with balanced input impedances, for which the proposed solution is still valid is given as,

$$U_1 \neq 0$$

$$U_2 = U_3 = 0$$

$$z_1 = z_2 = z_3 \neq 0$$

Under unbalanced input voltages and unbalanced input impedances, the maximum level of imbalance for which the proposed solution is still valid is given as,

$$U_1 \neq 0$$

$$U_2 = U_3 = 0$$

$$z_1 = 0$$

$$z_2 \neq z_3 \neq 0$$

From the above discussion, it follows that the three-phase PWM Boost Type Rectifier can operate from the single-phase supply as well (the special case of imbalance of the three-phase system). This is an extremely important result, since it means that the three-phase PWM Boost Type Rectifier can operate from the center-tapped transformer as well and still maintain high quality DC output voltage and input currents.

In this case, input voltages and impedances are given as,

$$|U_1| = |U_3|$$

$$phase(U_1) = 0^o$$

$$phase(U_3) = -180^o$$

$$U_2 = 0$$

$$z_1 = z_2 = z_3 \neq 0$$

B. The physical meaning of the proposed method

The proposed solution for harmonic elimination is based on the cancelation of the input pulsating power on three input inductances. The input instantaneous power can be expressed as,

$$p(t) = u_1(t)i_1(t) + u_2(t)i_2(t) + u_3(t)i_3(t) - \\ \text{Constant term} + \text{Pulsating term}$$

The instantaneous power on three input inductances can be expressed as,

$$p_l(t) \;=\; u_{l1}(t)i_1(t) + u_{l2}(t)i_2(t) + u_{l3}(t)i_3(t) = \\ \text{Pulsating Term}$$

The power that goes to the converter is given by,

$$Pc = p(t) - p_l(t) =$$

$$\text{Constant Term} + \text{Pulsating Term - Pulsating Term} = \\ \text{CONSTANT}$$

Since the pulsating power gets cancelled on three input impedances, the constant power supplies the converter and therefore the harmonics are completely eliminated.

III. CONTROL METHOD

Based on the analysis of the open loop configuration presented above, a feed forward control method is proposed. Input voltages as well as input impedances have to be measured . Based on this information and a DC bus error, reference currents are calculated according to equations (18), (23) and (25) which become reference signals for the hysteresis controller [3]. Only one PI controller is utilized, which has been shown to be sufficient for good regulation. The proposed control method is shown in more detail on Fig.2.

IV. SIMULATION RESULTS

The operation of the three-phase PWM Boost Type Rectifier supplied from the single phase supply with unbalanced impedances (Fig.3) was built in SABER. Plots on Fig.4 and Fig.5 show the controlled output DC voltage and actual line currents. Parameters used in simulation are shown in Table I. Input currents are unbalanced, as expected, to cancel the pulsating power coming from the input [1]. The converter operates at unity power factor and it shows stable behavior in spite of the extreme level of unbalance. The operation of the three-phase PWM Boost Type Rectifier supplied from the center-tap transformer is shown on Fig.6. The plot on Fig.7 shows controlled output DC voltage and actual input currents. Parameters used in simulation are shown in Table II.

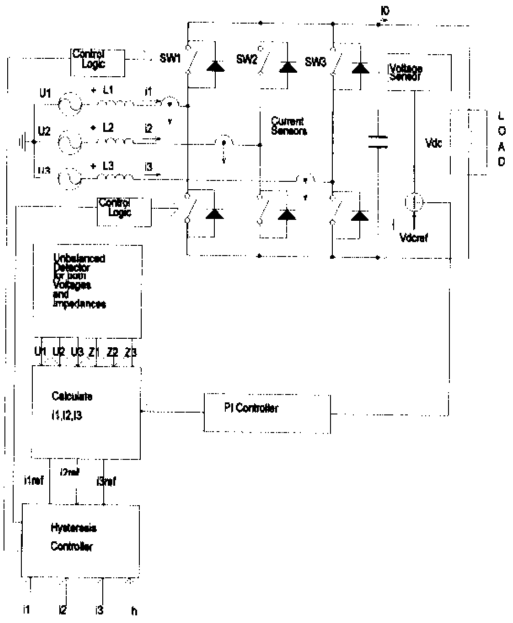

Fig. 2. The proposed closed loop solution for input-output harmonic elimination under unbalanced input voltages and unbalanced input impedances.

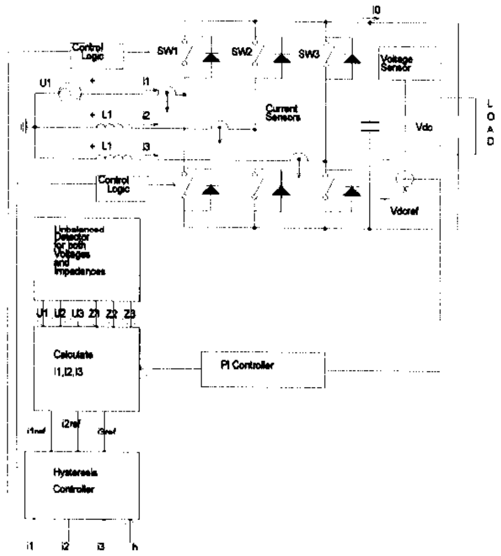

Fig. 3. PWM Boost Type Rectifier supplied from the single-phase supply.

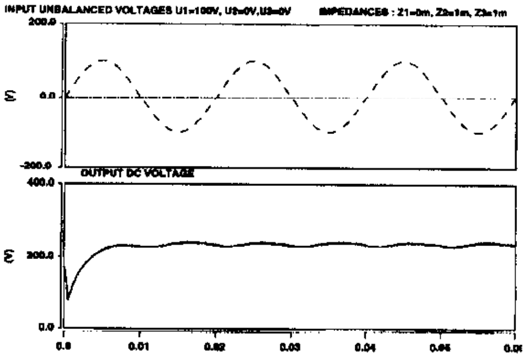

Fig. 4. Input voltages and output DC voltage when PWM Boost Type Rectifier is supplied from the single-phase supply (simulation results).

TABLE I

Parameters used in simulation

Parameter	Value	Parameter	Value
Input supply voltages	$U_1 = 100\angle 0$ $U_2 = 0$ $U_3 = 0$	DC-link capacitor, C	$100uf$
DC-link voltage, V_{dc}	$220V$	Output resistive load, R	100Ω
Per-phase line inductance, L	$L_1 = 0$ $L_2 = L_3 = 1mH$	Fundamental frequency, f	$60Hz$

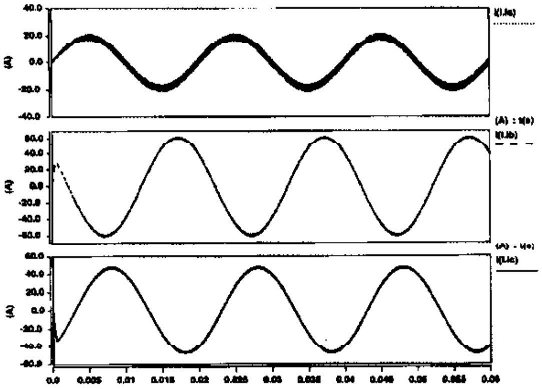

Fig. 5. Input currents when PWM-Boost Type Rectifier is supplied from the single-phase supply (simulation results).

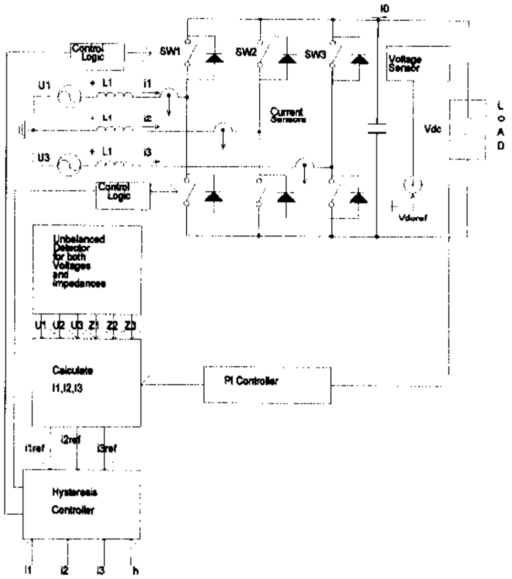

Fig. 6. PWM Boost Type Rectifier supplied from the center-tapped transformer.

TABLE II

Prameters used in simulation

Parameter	Value	Parameter	Value
Input supply voltages	$U_1 = 100\angle 0$ $U_2 = 0$ $U_3 = 100\angle -180$	DC-link capacitor, C	$100uf$
DC-link voltage, V_{dc}	$220V$	Output resistive load, R	100Ω
Per-phase line inductance, L	$L_1 = L_2 = L_3 = 1mH$	Fundamental frequency, f	$60Hz$

V. CONCLUSIONS

This paper proposes a new control method for input output harmonic elimination of the PWM Boost Type Rectifier under unbalanced input voltages and unbalanced input impedances The theoretical approach for complete input output harmonic operation of the PWM Boost Type Rectifier with adjustable power factor is presented. The range of unbalance in input voltages and input impedances is analyzed in detail. Based on the analyses in the open loop configuration, the closed loop solution is proposed. An important result that follows is the possible operation of the three phase PWM Boost Type Rectifier from the single phase supply, being the

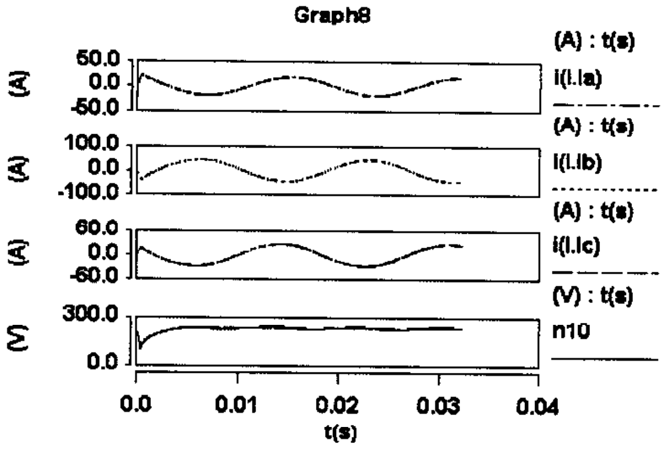

Fig. 7. Input currents and output DC voltage when PWM Boost Type Rectifier is supplied from the center-tapped transformer (simulation results).

special case of unbalance in input voltages.

The simulation results show excellent behavior and high quality of input and output waveforms in spite of the extreme unbalance in input voltages and input impedances.

REFERENCES

[1] A. V. Stankovic and T. A. Lipo, " A Novel Control Method for Input Output Harmonic Elimination of the PWM Boost Type Rectifier Under Unbalanced Operating Conditions", IEEE-APEC, Conf. Rec., pp 666-669, 2000.

[2] L. Moran, P.D. Ziogas, and G. Joos, " Design Aspects of Synchronous PWM Rectifier-Inverter System Under Unbalanced Input Voltage Conditions," IEEE Transactions on Industry Applications, vol. 28, no. 6, pp.1286-1293, Nov./Dec. 1992.

[3] J.W. Wilson, "The Forced-Commutated Inverter As a Regenerative Rectifier," IEEE Transactions on Industry Applications, vol. IA-14, no. 4, pp. 335-340, July/Aug. 1978.

[4] D.M. Brod and D.W. Novotny, "Current Control of VSI-PWM Inverters," IEEE Transactions on Industry Applications," vol. IA-21, no. 4, pp. 769-775, Nov./Dec. 1984.

[5] P. Rioual, H. Pouliquen, and J.P Louis, "Regulation of a PWM Rectifier in the Unbalanced Network State," IEEE-PESC, Conf. Rec., pp. 641-647, 1993.

[6] P. Enjeti and S.A. Choudhury, "A new Control Strategy to Improve the Performance of a PWM AC to DC Converter Under Unbalanced Operating Conditions," IEEE-PESC Con.Rec., 1991, pp. 382-389.

[7] T.A. Lipo, "Recent Progress and Development of Solid State AC Motor Drives," IEEE Transactions on Power Electronics, vol. 3, no. 2, pp. 105-117, April 1988.

[8] R.P. Stratford, D.E. Steeper, "Reactive Compensation and Harmonic Supression for Industrial Power Systems Using Thyristor Converters", 1974 IAS Annual Meeting, 21 pp.