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Fuzzy Controller for Circulating Current in Parallel Three Phase PWM Converters under Generalized Unbalanced Operating Conditions

[1] M. Madhavi, [2] R. Madhavi
[1] PG Student, [2] Assistant Professor
Department of Electrical and Electronics Engineering, Annamacharya Institute of Technology and Sciences, Tirupathi, Andhra Pradesh-517507, INDIA

***Abstract*: -- The use of common dc-link parallel three-phase PWM converter topology owing to advanced features & applications has become more popular, This paper proposes another control scheme for parallel three phase pulse width modulation (PWM) converters under generalized lopsided working conditions. When three-phase PWM converters are connected in parallel there exist circulating current, which result in current distortion and harmonic loss in parallel module and degrade the overall performance of the parallel system. An average model of the parallel system in positive-sequence synchronous reference frame (PSRF) is derived to dissect the impact of generalized unequal working conditions in AC side. It is seen that the variance in network frequency & the unbalance factors in filter inductance won't just offer ascent to negative-sequence circulating current, additionally add to creating zero-sequence circling current (ZSCC) with the coupling between the active-reactive system. The negative-sequence circling current can be restrained by suppressing the negative-sequence parts in AC output currents of parallel modules with a proportional integral resonant (PIR) controller. An enhanced feed forward system and a fuzzy controller for ZSCC control are proposed for unequal working conditions. The unsettling influences in ZSCC caused by unbalance factors in filter inductance can be rejected with feed forward methodology. The proposed plan with a PIR, Improved feed forward & fuzzy controller can successfully stifle the circulating currents between the parallel modules and therefore, the distortions in output currents can be enormously diminished..**

Index Terms— Parallel three-phase PWM converter & Average model in PSRF mode, Generalized unequal operating conditions, Circulating current control, PIR & Improved feed forward with fuzzy logic controller.

I. INTRODUCTION

Three-phase pulse width modulation (PWM) converter has been broadly utilized in distributed generation systems for achieving fast dynamic response & allows the processing of active and reactive power from the generator to the load and vice versa, depending on the application [1-3]. Attributable to its advanced features, and its parallel association topology is getting to be noticeably famous used to expanding the power rating of distributed generation system because of its simplicity, low cost and high flexibility. In any case, these features are not really accomplished when the converters are directly connected between normal dc and ac buses under generalized working states of unequal network supply and uneven ac filter inductance. The main concern in a parallel system is the currents circulating between the parallel modules [4], [5].Since the circulating current generation is sensitive to output voltage differences [7] & the dead-time effects, which are known to cause load-dependent distortion to inverter output voltages [[4]- ref [12]]. The zero-sequence component in circulating currents is the major problem under balanced operating conditions, the mechanism of circulating current has been analyzed in previous work [18],[19], & the relationships between switching pattern and zero-sequence circulating current (ZSCC) is analyzed in detail by [6].

Traditionally, in order to avoid this circulating current problem which includes the negative-sequence and zero-sequence components can effectively eliminated by isolating transformers as the circulating currents paths are made open circuits[20],These transformers are designed with a certain winding turns-ratio and a certain phase shift, so that the concerned harmonics can be cancelled in the other side. However, these transformer is heavy and bulky in parallel module especially for a high-power application. Similar problems will be encountered by using separate dc supply. For parallel systems with both common dc-link and ac bus to reduce the costs and size, inter-phase reactors may be used to provide high zero-sequence impedance for circulating currents [22]. Nevertheless, the reactors cannot prevent low-frequency components in the circulating current. Therefore, a direct connection between the power converter module and power system is desirable.

To reduce the ZSCC, special PWM techniques have been proposed. The discontinuous space modulation based interleaved PWM method would effectively reduce the circulating current with a power-factor-correction circuit, whereas it will result in high current ripple in parallel modules [7]. Instead, a harmonic elimination pulse width modulation (HEPWM) method proposed by [8] can overcome the current ripple disadvantage and effectively eliminate both the high frequency and low frequency components in ZSCC. However, it suffers from high switching losses. Due to the fact that the ZSCC is mainly affected by zero vectors employed in each PWM cycle, a multicarrier PWM modulation technique without using zero vectors is proposed to mitigate the ZSCC [9]. The ZSCC can be suppressed to some extent by reducing the common-mode voltage. An average model of the parallel converters in rotating coordinates is introduced in [10], instead of avoiding using zero vectors, the popular space vector pulse width modulation (SVPWM) modulation technique can effectively suppress the zero-sequence component in circulating current by adjusting the distribution of two zero vectors in each PWM cycle with a proportional integral (PI) controller [11]. However, the traditional PI method can't effectively reject the disturbances caused by unbalance factors in filter inductance. Nonlinear control methods were also presented to resist the circulating current [12], but the algorithms are too complicated to implement. The operation of three-phase PWM converter in unbalanced condition has been widely researched [13-17], but the operation of paralleled converters has not been paid much attention. Apart from zero-sequence component in circulating currents, unbalanced grid supply would probably generate negative-sequence circulating current between parallel modules. As a matter of fact, the negative-sequence circulating current is generated mainly because of the negative-sequence components in output currents of the parallel modules. Thus, coordinate control method has been proposed in and [19] to inhibit the negative-sequence circulating current by suppressing the negative-sequence components in currents. Because of the capability of achieving zero steady-state error at AC frequency, resonant controller is now used in AC system, especially for grid current control in PWM converter system [23-25], but its application for circulating current control has not been published. An open-loop control method is proposed in [5] and the control methods on zero-sequence circulating current caused by dead time effect [4] has been developed. Circulating current suppression performance can be enhanced by expanding the bandwidth of zero-axis current loop [26]. Characterization of steady state current ripple under inductance mismatches have been analyzed in [27]. Grid current distortion in parallel module with carrier interleaving is analyzed in [28], Compared to the work of [26], PIR control scheme for the parallel three phase PWM converters under generalized operating conditions was proposed [29].

This paper proposes another control scheme for parallel three phase pulse width modulation (PWM) converters under generalized lopsided working conditions. An average model of the parallel system in positive-sequence synchronous reference frame (PSRF) is derived to dissect the impact of generalized unequal working conditions in AC side. It is seen that the variance in network frequency & the unbalance factors in filter inductance won't just offer ascent to negative-sequence circulating current, additionally add to creating zero-sequence circling current (ZSCC) with the coupling between the active-reactive system. A proportional integral resonant (PIR) controller is adopted to inhibit the negative-sequence circulating current by suppressing the negative-sequence components in output currents. The unsettling influences in ZSCC caused by unbalance factors in filter inductance can be rejected with feed forward methodology. An enhanced feed forward system and a fuzzy controller for ZSCC control are proposed for unequal working conditions. The proposed plan with a PIR, Improved feed forward & fuzzy controller can successfully stifle the circulating currents between the parallel modules and therefore, the distortions in output currents can be enormously diminished. The feasibility and advantage of the proposed scheme are verified through experimental analysis.

The rest of the paper is sorted out as. In Section II, the meaning of circulating currents and an average model of parallel three phase converters with SVPWM technique under summed up uneven working conditions is determined in PSRF & the impact of un modulation filter channel inductance on the dynamic responsive current system and ZSCC control system is dissected. In Section III, The guideline of proposed circling current procedure in view of feed forward technique with fuzzy logic controller and PIR controller is presented in detail. In section IV finishes up proposed control scheme with the experimental results and In Section Ⅴ concludes the paper.

II. MODEL OF PARALLEL THREE PHASE CONVERTERS UNDER GENERALIZED UNBALANCED OPERATING CONDITIONS

A. Theory of circulating current in parallel three phase converter

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In this paper, the parallel structure of three phase boost type PWM converter is shown in fig.1, with a SVPWM technique for illustrating the circulating current in parallel module. As shown in fig.1 the common dc-link converter which are in parallel module are connected to the ac grid through a channel inductance. The switches of parallel modules in the same phase are connected in series. Consequently, circulating current path is formed due to the fact that the switches of in different modules are connected in series [18]. Ideally, if the parallel converters with equal output currents are completely identical in parameters, uniformly modulated, no circulating current would be generated as the output voltages in the ac side have the same frequency, phase, and amplitude. However, generally in practical applications, while parallel module converters are usually designed to have the same parameters, tolerance in parameter dispersion is very common especially in the line inductance [27], which in return would result in different filter inductance and unequal measured values of output currents. Moreover, the synchronism between the carriers of different converters may be interfered. As a consequence, differences will occur in the output voltages of the parallel modules during the short switching process, both in amplitude and phase. Consequently, circulating current would be generated as asynchronous action emerges.

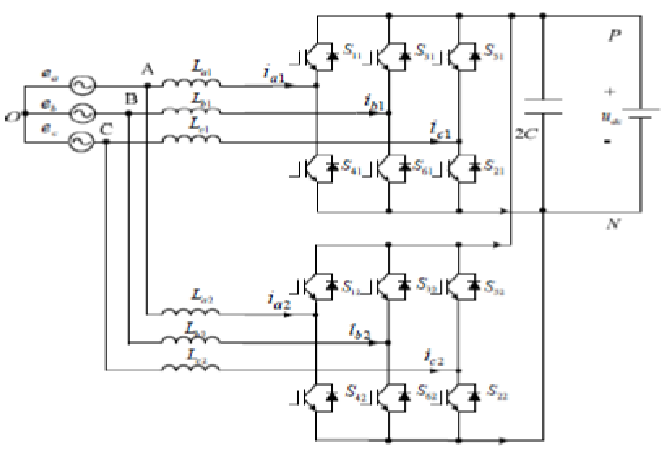

Fig.1 Topology structure of parallel connection system of three-phase PWM converter

In general, there exist two types of circulating currents Paths, i.e. the ZSCC paths and nonzero-sequence circulating Current paths. The zero-sequence component in the circulating currents is the major concern under balanced conditions, which can be defined as:

$$i_{zx} = (i_{ax} + i_{bx} + i_{cx})/3 \qquad (1)$$

Where x=1,2 is the number of parallel modules. And the circulating current in phase (k=a,,c) of converter 1 can be defined as:

$$i_{ck} = (i_{k1} - i_{k2})/2 \qquad (2)$$

The nonzero-sequence component in the circulating currents usually can be neglected under balanced conditions as output currents of the parallel modules are balanced. However, this is not really valid under the working conditions of unbalanced grid voltage and unbalanced ac channel inductance. Such a summed up unbalance condition is quite common in application and will result in appearance of negative sequence as well as odd harmonic components in the output currents, which would distort the output currents of parallel systems. The negative-sequence currents will probably contribute to generating nonzero-sequence component in circulating currents, and here we refer it to negative-sequence circulating current.

B. ZSCC with SVPWM Modulation Technique

The SVPWM modulation technique is widely applied in the control of three-phase PWM converters because of its advanced features including high dc voltage use and less distortions in ac side currents. When SVPWM is employed, the zero-sequence voltages of the parallel inverters may vary, thus producing difference in the zero-sequence voltage and giving rise to a zero-sequence circulating current [5]. Comparison among various PWM methods, SVPWM is superior to sinusoidal PWM.

Normally, the SVPWM modulator cannot independently control the three-phase fundamental modulation waveforms and the zero-sequence modulation waveform. When the power-sharing control system is working, the zero-sequence modulation waveforms of the parallel inverters vary with the fundamental voltages. A zero-sequence circulating current exists in the zero-sequence path when the complex power sharing of the inverters is different. The control vector Vs in each PWM cycle is synthesized by two adjacent non-zero vectors Vi (i=1, 2, 3, 4, 5, 6) and two zero vectors Vj (j =0, 7) as illustrated in Fig. 2.

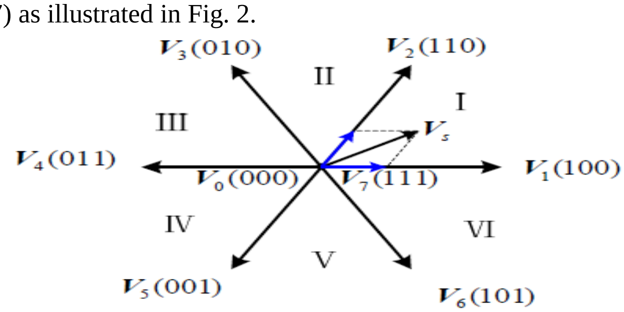

Fig.2 synthesis of control voltage vector with basic voltage vectors

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C. Average Model of the three-phase parallel converter To examine the impact of unbalance conditions on circulating current, a scientific model of the parallel system should be derived. From fig.1, pick the dc negative side as reference point, then from Kirchhoff¡¦s voltage, the parallel structure under summed up unequal working conditions can be described by the accompanying differential equation as:

$$L_{kx}\frac{di_{kx}}{dt} = e_k - d_{kx}u_{dc} + u_{ON} \qquad (3)$$

Where Lkx, ikx and dkx (k = a, b, c; x = 1, 2) are the channel inductance, current and the duty ratio of the top switch in phase k of converter x, respectively. To simplify the analysis, the resistor of the channel is dismissed. As a rule terms, the grid essential frequency voltage under uneven conditions can be communicated as:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = E_{pm}\begin{bmatrix} \cos\omega t \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} E_{nm}\begin{bmatrix} \cos\omega t \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \end{bmatrix} \qquad (4)$$

Where ω is the grid fundamental frequency, Epm and Enm are the amplitudes of positive-grouping and negative succession voltages, respectively. One of the most conventional solutions for the control of grid connected converters is the dq synchronous current controllers. This technique is based on the implementation of controllers that lies on rotating reference frames which are synchronized with the frequency component to be injected. If the fundamental component of the grid current must be injected, the synchronous reference frame (SRF) is synchronized with the fundamental positive-sequence voltage phase angle (θ+). The main advantage of using an SRF is that the measured ac currents and voltages of the proper sequence are transformed into dc magnitudes, in the so-called dq frame, by using Park's transformation. As long as dc magnitudes are involved, classical control techniques can be used in order to achieve the desired performance. In this paper we considered PSRF with a three dimensional non-singular matrix which can be defined as:

Where $xabc$ and $xdqz$ represent the ac variable and its transformed variable in PSRF, respectively. The components x ,q and xz are referred to active, reactive and zero-sequence components of $xdqz$ in PSRF, the transformation matrix is expressed as

$$x_{dqz} = T_{s\_r}.x_{abc} \qquad (5)$$

Where $xabc$ and $xdqz$ represent the ac variable and its transformed variable in PSRF, respectively. The components x ,$_q$ and x_z are referred to active, reactive and zero-sequence components of x_{dqz} in PSRF, the transformation matrix is expressed as:

$$T_{s\_r} = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin\omega t & -\sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Therefore, from (3)-(5), the parallel structure under generalized operating conditions can be described can be in PSRF expressed as:

$$\tilde{e_d} = Epm + Enm\cos 2\omega t$$
$$\tilde{e_q} = -Enm\cos 2\omega t$$
$$u_{dx} = \left(d_{ax}\cos\omega t + d_{bx}\cos\left(\omega t - \frac{2\pi}{3}\right) + d_{cx}\cos\left(\omega t + \frac{2\pi}{3}\right)\right)u_{dc}$$
$$u_{qx} = \left(-d_{ax}\sin\omega t - d_{bx}\sin\left(\omega t - \frac{2\pi}{3}\right) - d_{cx}\sin\left(\omega t + \frac{2\pi}{3}\right)u_{dc}\right)$$
$$u_{zx} = (d_{ax} + d_{bx} + d_{cx})u_{dc}/3 \qquad (6)$$

Where d,e~

e~ represent the active and reactive components of unbalanced grid voltage in PSRF and uzx is the zero-sequence component in output voltage. From the above analysis, It should be noted that coupling exist between the zero-sequence current system and the active-reactive current system [29]. When grid-voltage oriented vector control is considered, the dq-axis can be defined as active and reactive power axis respectively [26]. Then the active- reactive current system can be obtain from [29] is shown in fig.3.

The unbalance factors in channel inductance will lead oscillatory components, similar oscillatory terms will also appear in grid voltage components d,e~ e~ due to the existence of negative- sequence component in grid voltage. Additionally, when the SVPWM technique is adopted, the zero sequence output voltage at ac side in parallel will also exist the oscillatory components in the active-reactive current system. All these oscillatory terms will give rise to negative sequence currents in parallel module

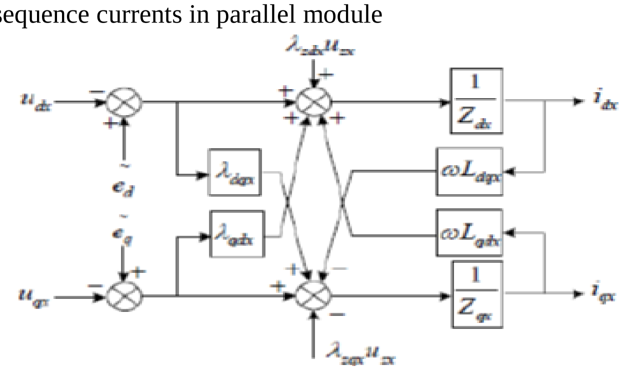

Fig. 3 Active-reactive current system in PSRF under generalized unbalanced operating conditions

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From fig.3 it can be noted asLdq , $Lqdx$, λdqx , λqdx , λzdx , λzqx is the coupling coefficients inside the active-reactive current system and between the active-reactive current system and ZSCC system. For the most part, the negative sequence currents will bring about unequal yield currents and cause different switching misfortunes in three bridge of a single converter. Besides, it will most likely cause negative succession segment in circulating currents. According to the theory depicted in [18], the negative-sequence circulating current can be inhibited by stifling the negative-sequence components in output currents.

The ZSCC is a major concern for the converters in the parallel structure as it will mutilate the yield currents and undermine the execution of the system. A normal model of the ZSCC system under summed up lopsided working conditions will be good in analysing the affecting factors of zero-sequence segment and developing improved control algorithm. From (6) one can see that the ZSCC system is combined with the dynamic responsive current system. Decoupling would be complicated and not practical. To acquire a proper mathematical model for the zero-sequence system, suppose both the active and reactive currents are well controlled with negative-sequence components eliminated. The zero-sequence voltage drop on the channel inductance can be given as:

$$u_{Lzx} = \begin{bmatrix} \omega L_{ax} & \omega L_{bx} & \omega L_{cx} \end{bmatrix} \begin{bmatrix} -\sin \omega t & -\cos \omega t \\ -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\cos\left(\omega t - \frac{2\pi}{3}\right) \\ -\sin\left(\omega t + \frac{2\pi}{3}\right) & -\cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{dx} \\ i_{qx} \end{bmatrix} \quad (7)$$

Where as $\Delta uLz = uLz1 - uLz2$ as the the difference in inductance zero-sequence voltages between parallel modules and $\Delta dz = dz1 - dz2$ as the zero-sequence duty ratio difference, then the average model of ZSCC system can be calculated as:

$$(L_{m1} + L_{m2})\frac{di_{z2}}{dt} = \Delta u_{Lz} + \Delta d_z u_{dc} \quad (8)$$

III. PROPOSED CONTROL STRATEGY FOR CIRCULATING CURRENT SUPRESSION

A. Control of Negative-sequence circulating current To restrain the negative-sequence circulating current, it should be made to stifle the negative-succession parts. The unbalance factors in channel inductance and grid frequency components with the active-reactive current system will lead oscillatory components, similar oscillatory terms will also appear in d, q e ~ e ~ due to the existence of negative-sequence component in grid voltage. Conventionally, a PI controller can be embraced in PSRF to control the active-reactive currents provided that the channel inductance and system voltage are adjusted. Unfortunately, since a negativesuccession segment shows up as oscillatory ac part in PSRF, the PI controller is not able to stifle it without steady state error. To smother the negative-sequence current, a resonant controller can be reinforced to the traditional PI controller i.e. PIR controller. It can be expressed as:

$$G_c(s) = k_p + \frac{k_i}{s} + \frac{k_r s}{s^2 + \omega_r s/Q + \omega_r{}^2} \quad (9)$$

Where kp, ki and kr are the proportional, integral, and resonant gain parameters of the PIR controller, respectively, and ωr is the resonant frequency of the controller while Q can be defined as the quality factor of the controller. The control block diagram of negative-sequence current system is displayed in Fig.4. The outputs of current controllers can be calculated as:

$$u_{dx} = -\left(k_p + \frac{k_i}{s} + \frac{k_r s}{s^2+\omega_r s/Q+\omega_r{}^2}\right)\left(i_{dx\_ref} - i_{dx}\right) + \omega L_{mx} i_{qx} + \tilde{e_d}$$

$$u_{qx} = -\left(k_p + \frac{k_i}{s} + \frac{k_r s}{s^2+\omega_r s/Q+\omega_r{}^2}\right)\left(i_{qx\_ref} - i_{qx}\right) - \omega L_{mx} i_{dx} + \tilde{e_q} \quad (10)$$

Where x=1, 2 represent the number of converter 1 and converter 2, respectively

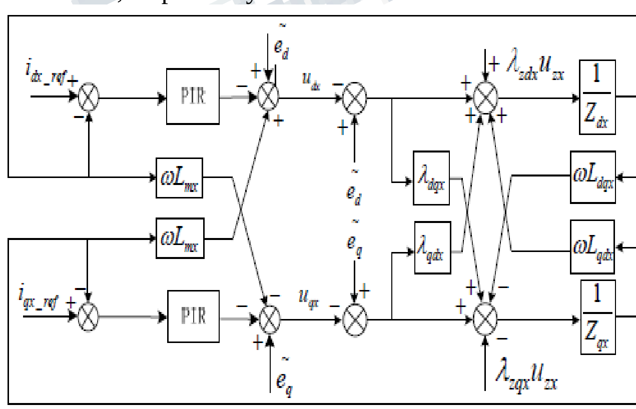

Fig.4. control block diagram of negative-sequence current system in PSRF

B. Control of Zero-sequence circulating current The SVPWM modulated technique vector distribution when control vector Vs lies between the non-zero vectors $V4$ and $V6$ is represented in Fig.5 with a control variable y to regulate the duration of zero vectors $V0$ and$V7$. Where Ts is time span of a PWM cycle, $d0$ is the duty ratio of zero vector and$d1$, $d2$represent the duty ratios of the two nonzero vectors

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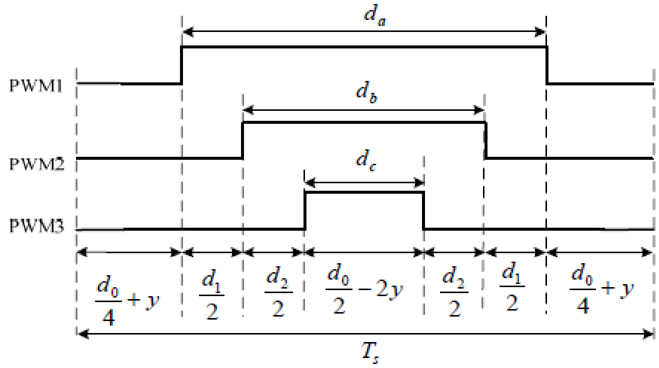

Fig.5. Distribution of vectors with zero-vector correction variable adopted

The control variable will redistribute the zero vectors in a PWM cycle, however it will not influence the distinctions in phase duty ratios. Subsequently, the execution of active reactive current system of each individual converter won't be influenced. In a two converter parallel system, just a single ZSCC exists. Hence, by stifling the ZSCC in one of the parallel modules, the zero-sequence component in yield current can be adequately dispensed with consequently. Here we choose converter 2 as the objective with control variable$y2$, and converter 1 embraces the ordinary SVPWM 5 adjustment method, i.e. $y1$ = 0. Then the simplified ZSCC system under generalized unbalanced operating conditions based on the average model of ZSCC is shown in fig.6.

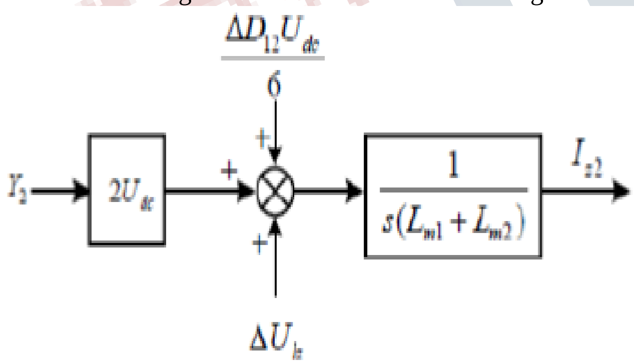

Fig.6. ZSCC system under generalized unbalanced operating conditions

Ideally the ZSCC loop of the modular designed parallel system is a first order system independent of the active reactive current system. A simple PI controller to suppress the circulating current of zero-sequence current loop with filter inductance unbalanced system is shown in fig.7. And thecirculating current control variable can be obtained as:

$$y_2 = \left(K_{pz} + \frac{K_{iz}}{s}\right)\left(i_{z2\_ref} - i_{z2}\right) \qquad (11)$$

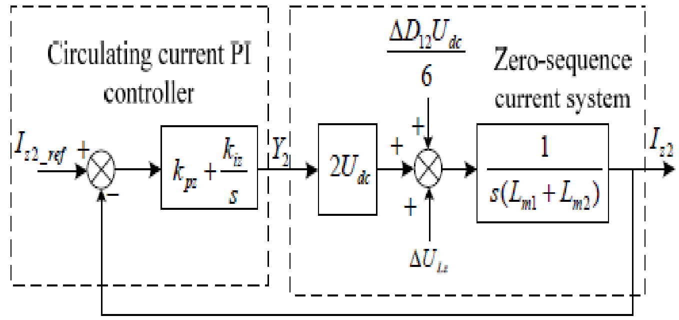

Fig.7. Zero-sequence current loop with filter inductance unbalanced with PI controller

Where i_{z2_ref} is the reference value of ZSCC, and K_p , K_{iz} are the parameters of the circulating current PI controller. Based on the analysis aforementioned, the angular frequency of Δu_{Lz} is , just the angular frequency of grid fundamental component, which is usually lower than the bandwidth of ZSCC control system. In a word, as depicted in Fig.7, both Δu_{Lz} and Δd_{12} will cause significant disturbances to the ZSCC system. Consequently, the suppressing performance of PI controller would be deteriorated.

To beat the disservice of conventional PI technique in smothering ZSCC and wipe out the effects caused by Δu_{Lz} andΔd_{12} , a feed forward system on the premise of PI strategy is proposed. The feed forward quantity $\Delta d_{12}12$ /and $\Delta u_{Lz}2u_{dc}$ /are utilized to dismiss the disturbances caused by, Δu_{Lz} andΔd_{12}, respectively. With the proposed feed forward control strategy, the circulating current control variable can be acquired as:

$$y_2 = \left(K_{pz} + \frac{K_{iz}}{s}\right)\left(i_{z2\_ref} - i_{z2}\right) - \frac{\Delta d_{12}}{12} - \frac{\Delta u_{lz}}{2u_{dc}} \qquad (12)$$

In steady state, the currents in dq frame are constant, so it can be seen that the disturbances caused by unbalance filter inductances is the fluctuation in grid frequency. So the fluctuate in grid frequency can be suppressed by resonance controller, the ZSCC controller is as follows

$$y_2 = \left(K_{pz} + \frac{K_{iz}}{s} + \frac{2K_r\omega_c s}{s^2+2\omega_c s+\omega_0{}^2}\right)\left(i_{z2\_ref} - i_{z2}\right) - \frac{\Delta d_{12}}{12} \qquad (13)$$

The system control block diagram of the proposed control scheme for the parallel system is shown in Fig.9. The active and reactive currents are controlled by PIR controllers which can effectively inhibit the negative-sequence components in output currents and suppress the negative-sequence circulating current. It should be noted that the outputs $U_{\alpha x\_ref}$ and $U_{\beta x\_ref}$ are the Clarke transformation of U_{dx} andU_q , respectively. And a notch filter is utilized as a part of the Phase Locked Loop (PLL) to follow the phase point of positive-grouping segment in the grid voltage. The transfer function of the notch filter is

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$$F(s) = \frac{s^2+\omega_n{}^2}{s^2+\omega_n/Q_f+\omega_n{}^2} \qquad (14)$$

Where $\omega n = 2\omega$ (ω is the grid fundamental angular frequency) and $Qf = 10$. The ZSCC control block is shown in the shaded area. The ZSCC in converter 2 is smothered to dispense with the zero-grouping segment in yield current of the parallel modules. The distinction between $iz2$ and its reference value is fed into the fuzzy controller. Then, the feed forward amount of $\Delta d12$ is acquired by figuring the time spans of two nonzero vectors $t1x$ and $t2x$ ($x = 1,2$) in each PWM cycle as $d1x = t1xTs \,/$, $d2x = t2xTc/$. All the while, condition (7) is utilized to get another feed forward amount $\Delta ulz2udc\,/$. At that point the ZSCC control variable $y2$ is used to modify the zero-sequence duty ratio of converter 2 by redistributing the time span of zero vectors in each PWM cycle.

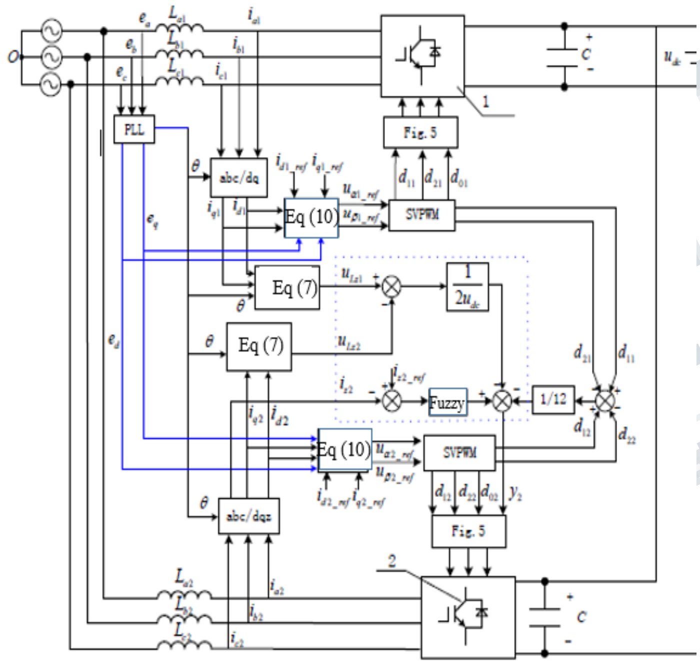


Fig. 8 System block diagram of the parallel three phase PWM structure with improved feed forward and fuzzy circulating current controller

The proposed fuzzy controller scheme is direct method which is most commonly used in application due to its simple structure of min-max operations. A Typically fuzzy logic control system is consists mainly three components they are fuzzification interface, fuzzy set with membership function and defuzzification interface. Here we are considered two inputs and one output parameter. These two input parameters are fuzzified with utilization of pre-characterized input enrollment capacities, which can have diverse shapes with the fuzzy sets and membership functions. After the fuzzy sets operation it will fed to the defuzzification and finally gives the output. The proposed scheme can be applied to three-phase PWM converter parallel system and the accurate information of filter inductance in parallel modules are the key factors in ensuring the circulating current suppression performance is achieved.

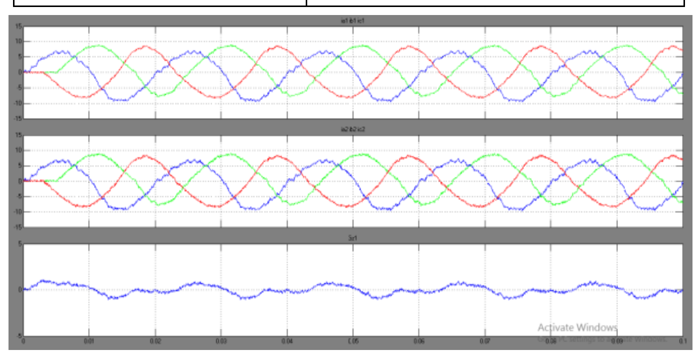
IV. TEST RESULTS

To verify the validity of the theoretical analysis and the effectiveness of the proposed scheme, the proposed scheme of two-paralleled converters is implemented in a MATLAB Simulation with some specific parameters shown as Table I. In order to illustrate the validity of better performance of the proposed method, the different zero **6** sequence circulating current control methods are compared by considering the generalized unbalanced operating conditions [29]. Method-1 is conventional PI controller. Method-2 is PI and improved feed-forward control method. Method-3 is PIR and feed-forward control method. Method-4 fuzzy controller with improved feed forward method.

Table I

Experimental Parameters

DC bus voltage	450V
AC line voltage	200V
Unbalanced AC voltage	*U*ab=200V, *U*bc=173V, *U*ca=100V.
Fundamental frequency	50Hz
Current reference	*I*d1_ref=*I*d2_ref=10A(RMS), *I*q1_ref=*I*q2_ref=0
Switching frequency	5kHz
Sampling frequency	10kHz
Inductor of converter1	*L*a1=*L*b1=*L*c1=6mH
Inductor of converter2	*L*a2=6mH, *L*b2=4mH, *L*c2=2mH



(a) Method-1

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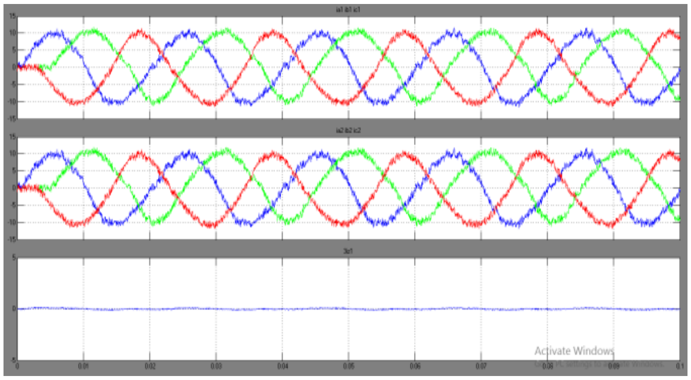
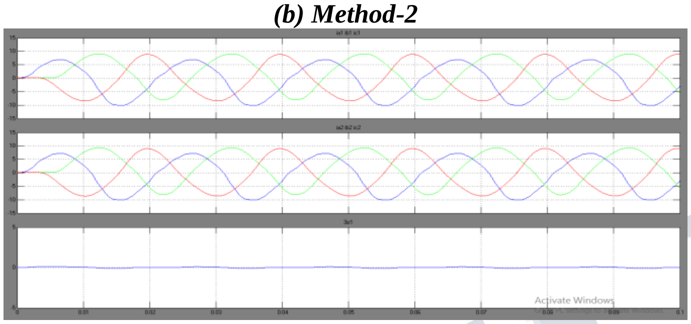
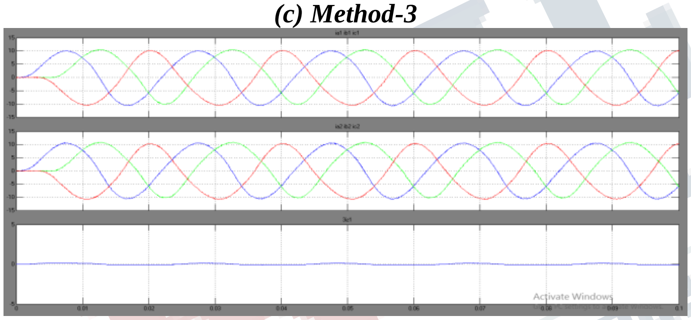


(b) Method-2



(c) Method-3



(d) Method-4

Fig.9 Experimental results of circulating current controlled in unbalanced operating conditions

Fig.9 shows the test results of different control methods for the circulating current suppression by considering the unbalanced factors. From fig. 9(a) we can analyze that because of the unbalance zero sequence voltage of inductance and the duty ratio will causes significant disturbances. Consequently the PI controller would be deteriorated. As shown in Fig.9 (b) it will overcome the problem faced on traditional PI method with a feed forward strategy to eliminate the disturbances. As shown the unbalance channel inductance will cause significant disturbances to converter output currents. The active and reactive current PI controller can't realize controlling negative-sequence currents without steady-state error, resulting in unbalanced output currents in the parallel modules. In steady state, the currents in dq frame are constant, so it can be seen that the disturbances caused by unbalance filter inductances is the fluctuation in grid frequency. So the fluctuate in grid frequency can be suppressed by resonance controller, i.e. is PIR with a feed forward controller as shown in Fig.9(C). the proposed method of an active-reactive currents are controlled by PIR in controlling the negative sequence components, and the improved feed forward quantity with a fuzzy controller to zero sequence circulating current suppression has the better performance as compared to other methods. Table II shows the effective performance of the proposed scheme to suppress the circulating current in parallel module.

Table II
Circulating current suppression

Methods	Negative-sequence circulating current		Zero-sequence circulating current	
	Conv.1	Conv.2	Conv.1	Conv.2
Method-1	1.38	2.28	3.64	3.64
Method-2	1.47	2.44	1.69	1.69
Method-3	0.28	0.49	1.38	1.37
Method-4	0.28	0.63	1.15	1.22

V. CONCLUSION

This paper proposes another control scheme for parallel three phase pulse width modulation (PWM) converters under generalized lopsided working conditions. An average model of the parallel system in positive-sequence synchronous reference frame (PSRF) is derived to dissect the impact of generalized unequal working conditions in AC side. It is seen that the variance in network frequency & the unbalance factors in filter inductance won't just offer ascent to negative- sequence circulating current, additionally add to creating zero-sequence circling current (ZSCC) with the coupling between the active-reactive system. The negative-sequence circling current can be restrained by suppressing the negative sequence parts in AC output currents of parallel modules with a proportional integral resonant (PIR) controller. An enhanced feed forward system and a fuzzy controller for ZSCC control are proposed for unequal working conditions. The unsettling influences in ZSCC caused by unbalance factors in filter inductance can be rejected with feed forward methodology. Improved circulating currents suppression performance can be achieved, and as a result, the distortions in output currents of parallel modules could be greatly reduced. Test results which is implemented in MATLAB simulation validate the performance and effectiveness of the proposed scheme. **7**

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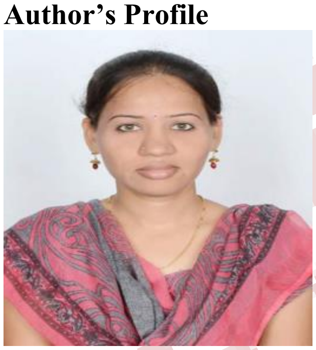
Author's Profile



M. Madhavi was born in AP, India in 1993. Currently she is studying her Post graduate degree in Annam Acharya Institute of Technology & Sciences, Tirupathi affiliated to Jawaharlal Nehru Technological University Anantapur in Electrical and Electronics Engineering with specialization in Electrical Power Electronics. Her area of interest include power Electronics and applications.

Mrs. R. Madhavi, she is currently working as Assistant Professor in Electrical and Electronics Engineering, Annamacharya Institute of Technology & Sciences, Tirupati. She has 2 years of teaching experience. Her area of interest is power Electronics and drives.