Control of Parallel Three Phase PWM Converters By Using An Improved Feed-Forward Strategy And A PIR Controller

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Abstract*- This paper proposes another control plot for parallel three phase pulse width modulation (PWM) converters under summed up unbalanced working conditions. A normal model of the parallel system in positive-sequence synchronous reference frame (PSRF) is determined to break down the impact of summed up unbalanced working conditions in AC side. It is seen that the unbalance factors in filter inductance won't just give rise to negative-sequence circuiting current, additionally contribute to creating zero-sequence circuiting current (ZSCC). The negative-sequence circuiting current can be restrained by stifling the negative-sequence segments in AC output current of parallel modules with a proportional integral resonant (PIR) controller. An Improved feed-forward methodology and a PIR controller for ZSCC control are proposed for unbalanced working conditions. The disturbance in ZSCC caused by unbalance factors in filter inductance can be rejected with feed forward system. Since the disturbance in ZSCC is the fluctuation in grid frequency which can be smothered by resonant controller, so a PIR controller is received in ZSCC controller. The proposed plan can viably smother the circulating current between the parallel modules and accordingly, the contortions in output currents can be enormously lessened. Exploratory outcomes affirm the execution and viability of the proposed strategy.*

Keywords- parallel three-phase PWM converters; circulating currents control; generalized unbalanced operating conditions, negative-sequence circulating current, feed-forward, PIR controller

I. INTRODUCTION

THREE-PHASE pulse width modulation (PWM) converter has been generally employed in disturbed generation systems [1-3] attributable to its propelled components, and its parallel connection topology is getting to be noticeably famous used to increasing the control rating of disturbed generation systems because of its straightforwardness, minimal effort and high flexibility. In any case, these highlights are not really accomplished when the converters are straightforwardly connected between regular dc and ac buss under summed up working states of unbalanced grid supply and unbalanced ac filter inductance. The principle worry in a parallel system is the current circulating between the parallel modules.

The zero-sequence segment in circuiting currents is the real issue under balanced working conditions, the connections between switching pattern and zero-sequence circuiting current (ZSCC) is broke down in detail by [6]. To lessen the ZSCC, unique PWM methods have been proposed. The discontinuous space modulation based interleaved PWM technique would adequately decrease the circuiting current with a control factor-correction circuit, though it will bring about high current swell in parallel modules [7]. Rather, a harmonic elimination pulse width modulation (HEPWM) technique proposed by [8] can beat the present current ripple disadvantage and effectively eliminate both the high frequency and low frequency components in ZSCC. Be that as it may, it experiences high switching losses. A multicarrier PWM modulation strategy without utilizing zero vectors is proposed to moderate the ZSCC [9]. The ZSCC can be suppressed to some degree by diminishing the regular mode voltage. A normal model of the parallel converters in turning organizes is presented in [10], of abstaining from utilizing zero vectors, the prevalent space vector pulse width modulation (SVPWM) balance procedure can viably suppress the zero-sequence segment in circuiting current by changing the conveyance of two zero vectors in each PWM cycle with a relative basic (PI) controller [11]. In any case, the traditional PI strategy can't successfully dismiss the unsettling influences caused by unbalance factors in filter inductance. Nonlinear control strategies were too introduced to oppose the circulating current, however the calculations are excessively confused, making it impossible to actualize.

The operation of three-phase PWM converter in uneven condition has been broadly inquired about however the operation of paralleled converters has not been given careful consideration. The component of circulating currents has been investigated in previous works. Aside from zero-sequence part in circulating currents, uneven grid supply would presumably create negative-sequence circulating current between parallel modules. The negative-sequence and zero-sequence components can both be adequately wiped out by confining transformers as the circulating currents ways are made open circuits. Be that as it may, consequently, the parallel system will turn out to be expensive and massive. Comparative issues will be experienced by utilizing isolated dc supply [21]. For parallel systems with both regular dc-link and ac bus to diminish expenses and size, between phase reactors might be utilized to give high impedance to circuiting currents [22]. Indeed, the negative-sequence circulating current is created for the most part in view of the negative-sequence components in output currents of the parallel modules. Subsequently, arrange control strategy has been proposed in and [19] to restrain the negative-sequence circuiting current by smothering the negative-sequence segments in currents. Due to the ability of accomplishing zero steady state error at AC frequency, resonant controller is presently utilized as a part of AC system, particularly for system current control in PWM converter system [23-25], however its application for circuiting current control has not been distributed.

Contrasted with the work of [26], new control scheme for the parallel three phase PWM converters under summed up working conditions was proposed. A normal model of the parallel system in positive-sequence synchronous reference frame (PSRF) is inferred to investigate the impact of uneven working conditions on converter output currents in AC side. The unbalanced grid supply would cause negative-sequence components in the output currents and may likewise bring about negative-sequence circulating current. A proportional integral resonant (PIR) controller is embraced to inhibit the negative-sequence circulating current by stifling the negative-sequence components in output currents. In addition, it is discovered that the unbalance factors in filter inductance won't just offer ascent to the creating of negative-sequence circuiting current, additionally make disturbances to the ZSCC system, which will add to producing low-frequency segments in ZSCC. In addition, to dismiss the disturbances caused by unbalance factors in filter inductance to ZSCC system, improved zero-vector feed-forward method can be utilized. Since the feed- forward strategy depends on the parameter of filter inductance, and the ZSCC caused by unbalance filter is regularly in grid frequency, so a resonance controller in grid frequency can be utilized. Joined with traditional PI controller, a PIR controller in grid frequency for ZSCC control is received in this paper. Enhanced concealment execution can be accomplished with the proposed conspire and the distortions in output currents can be incredibly decreased. The attainability and favorable position of the proposed plot are checked through exploratory investigation.

II. MODEL OF PARALLEL THREE PHASE CONVERTERS UNBALANCED OPERATING CONDITIONS

The parallel structure of three phase boost-type PWM converters is appeared in Fig.1. The regular dc-link converter modules are connected with the ac grid through filter inductance. Accordingly, the circulating currents ways are framed due to the certainty that the switches of in various modules are connected in sequence. When all is said in done, there exist two sorts of circuiting currents ways, i.e. the ZSCC ways and nonzero-sequence circuiting current ways. The ZSCC ways, take phase a for instance, can be recorded as A-La1-S11-P-N-S42-La2-An and ALa2- S12-P-N-S41-La1-A. This kind of circuits are shaped by two switches and inductances in a similar period of various converters, the dc bus voltage is the main electromotive force contained in the circuits. Interestingly, the nonzero-sequence circulating current ways, for example,

O-A-La1-S11-P-N-S62-Lb2-B-O,O-A-La2-S12-P-N-S61-Lb1-BO, O-B-Lb2-S32-P-N-S41-La1-An O,O-B-Lb1-S31-P-N-S42-La2- An O contain two more ac phase voltages.

For the most part, practical applications, while modular converters are normally intended to have break even with estimations of parameters, resistance in parameter scattering is exceptionally normal, particularly in the line inductance [27], [28]. As a result, the estimations of three phase filter inductance are not entirely equivalent, which will prompt asynchronous activities in switches, and therefore, circuiting currents will be produced. Circuiting current in phase k (k=a, b, c) of converter 1 can be characterized as:

$$i_{ck} = \frac{i_{k1} - i_{k2}}{2} \qquad (1)$$

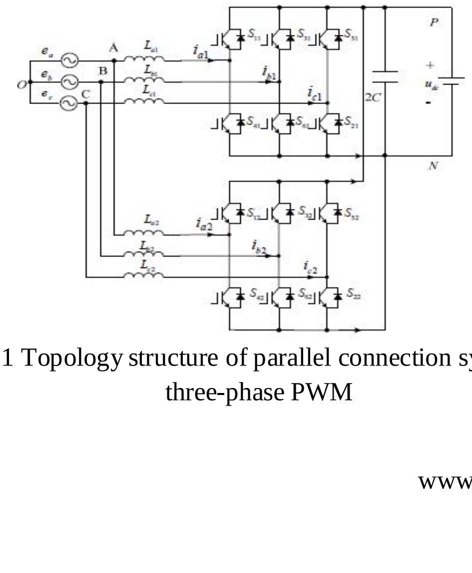


Fig.1 Topology structure of parallel connection system of three-phase PWM

Converter

What's more, the zero-sequence part in the circulating currents, which is the real worry under balanced conditions, can be characterized as:

$$i_{zx} = (i_{ax} + i_{bx} + i_{cx})/3 \qquad (2)$$

Where x = 1, 2 is the quantity of the parallel modules. The nonzero-sequence segment in the circulating currents normally can be dismissed under balanced conditions as output currents of the parallel modules are balanced. Be that as it may, this is not really valid under the working states of uneven grid voltage and unbalanced ac filter inductance. Such a summed up unbalance condition is very normal in application and will bring about appearance of negative-sequence and in addition odd harmonic components in the output currents, which would misshape the output currents of parallel systems. The negative-sequence currents will presumably add to producing non zero-sequence part in circulating currents, what's more, here we refer it to negative-sequence circulating current.

To dissect the impact of unbalance conditions on circulating currents, an explanatory model of the parallel system ought to be determined. Pick the dc negative side as reference point, at that point from Kirchhoff's voltage, the parallel structure under summed up unbalanced working conditions can be portrayed by the accompanying differential condition as:

$$\begin{cases} L_{ax}\dfrac{di_{ax}}{dt} = e_a - d_{ax}u_{dc} + u_{ON} \\ L_{bx}\dfrac{di_{bx}}{dt} = e_b - d_{bx}u_{dc} + u_{ON} \\ L_{cx}\dfrac{di_{cx}}{dt} = e_c - d_{cx}u_{dc} + u_{ON} \end{cases} \qquad (3)$$

Where l_{kx} , i_{kx} and d_{kx} (k =a, b, c, x=1, 2) are the filter inductance, current and the duty ratio of the best switch in phase k of converter x, individually. To improve the examination, the resistor of the filter is disregarded. By and large terms, the grid basic frequency voltage under unequal conditions can be communicated as:

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

Where ω is the grid principal angular frequency, E_{pm} *and* E_{nm} are the amplitudes of positive-sequence and negative-sequence voltages, separately. Expectedly, the ac variable can be transformed into the positive synchronous reference frame (PSRF) with a 3-dimensional nonsingular system as in (5):

$$x_{dqz} = T_{s\text{-}r} \cdot x_{abc} \qquad (5)$$

Where x_{abc} *and* x_{dqz} speak to the ac variable and its transformed variable in PSRF, individually. The components x_d , x_q *and* x_z are alluded to active, reactive and zero-sequence segments of x_{dqz} in PSRF, the transformation matrix is communicated as:

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

Along these lines, from (3) - (5), the parallel structure under summed up working conditions can be depicted can be in PSRF communicated as:

$$\begin{cases} \left(L_{mx} + \frac{1}{3}L_{\cos 2nx}\right)\dfrac{di_{dx}}{dt} - \dfrac{\omega}{3}L_{\sin 2nx}i_{dx} - \dfrac{L_{\sin 2nx}}{3}\dfrac{di_{qx}}{dt} \\ \quad -\omega\left(L_{mx} + \frac{1}{3}L_{\cos 2nx}i_{qx}\right) + \dfrac{2L_{\cos px}}{3}\dfrac{di_{zx}}{dt} = \tilde{e}_d - u_{dx} \\ \left(L_{mx} - \frac{1}{3}L_{\cos 2nx}\right)\dfrac{di_{qx}}{dt} + \dfrac{\omega L_{\sin 2nx}}{3}i_{qx} - \dfrac{L_{\sin 2nx}}{3}\dfrac{di_{dx}}{dt} \\ \quad +\omega\left(L_{mx} - \frac{1}{3}L_{\cos 2nx}\right)i_{dx} - \dfrac{2L_{\sin px}}{3}\dfrac{di_{zx}}{dt} = \tilde{e}_q - u_{qx} \\ \dfrac{L_{\cos px}}{3}\dfrac{di_{dx}}{dt} - \dfrac{\omega L_{\sin px}}{3}i_{dx} - \dfrac{L_{\sin px}}{3}\dfrac{di_{qx}}{dt} \\ \quad -\dfrac{\omega L_{\cos px}}{3}i_{qx} + L_{mx}\dfrac{di_{zx}}{dt} = -u_{zx} \end{cases} \qquad (6)$$

$$L_{mx} \stackrel{\Delta}{=} (L_{ax} + L_{bx} + L_{cx})/3$$

$$L_{\cos 2nx} \stackrel{\Delta}{=} L_{ax}\cos 2\omega t + L_{bx}\cos(2\omega t + 2\pi/3) + L_{cx}\cos(2\omega t - 2\pi/3)$$

$$L_{\sin 2nx} \stackrel{\Delta}{=} L_{ax}\sin 2\omega t + L_{bx}\sin(2\omega t + 2\pi/3) + L_{cx}\sin(2\omega t - 2\pi/3)$$

$$L_{\cos px} \stackrel{\Delta}{=} L_{ax}\cos\omega t + L_{bx}\cos(\omega t - 2\pi/3) + L_{cx}\cos(\omega t + 2\pi/3)$$

$$L_{\sin px} \stackrel{\Delta}{=} L_{ax}\sin\omega t + L_{bx}\sin(\omega t - 2\pi/3) + L_{cx}\sin(\omega t + 2\pi/3)$$

$$\tilde{e}_d = E_{pm} + E_{nm}\cos 2\omega t$$

$$\tilde{e}_q = -E_{nm}\cos 2\omega t$$

$$u_{dx} = \left(d_{ax}\cos\omega t + d_{bx}\cos(\omega t - \frac{2\pi}{3}) + d_{cx}\cos(\omega t + \frac{2\pi}{3})\right)u_{dc} = d_{dx}u_{dc}$$

$$u_{qx} = \left(-d_{ax}\sin\omega t - d_{bx}\sin(\omega t - \frac{2\pi}{3}) - d_{cx}\sin(\omega t + \frac{2\pi}{3})\right)u_{dc} = d_{qx}u_{dc}$$

$$u_{zx} = (d_{ax} + d_{bx} + d_{cx})u_{dc}/3 = d_{zx}u_{dc}$$

A. Model of the Active-reactive Current System

It ought to be noticed that coupling exist between the zero-sequence current system and the active-reactive current system. An exact model of the active-reactive current system is frequently good when planning current controllers. In view of the thought, the active-reactive current system can be gotten from (6) as the accompanying structure:

$$\begin{cases}\left(L_{mx}+\frac{1}{3}L_{\cos 2nx}-\frac{2L^2_{\cos px}}{9L_{mx}}\right)\frac{di_{dx}}{dt}+\omega\left(L_{mx}+\frac{1}{3}L_{\cos 2nx}+\frac{2L^2_{\cos px}}{9L_{mx}}\right)i_{qx}\\ +\left(\frac{2L_{\sin px}L_{\cos px}}{9L_{mx}}-\frac{L_{\sin 2nx}}{3}\right)\frac{di_{qx}}{dt}+\omega\left(\frac{2L_{\sin px}L_{\cos px}}{9L_{mx}}-\frac{L_{\sin 2nx}}{3}\right)i_{dx}\\ =\tilde{e}_d-u_{dx}+\frac{2L_{\cos px}}{3L_{mx}}u_{zx}\\ \left(L_{mx}-\frac{1}{3}L_{\cos 2nx}-\frac{2L^2_{\sin px}}{9L_{mx}}\right)\frac{di_{qx}}{dt}+\omega\left(L_{mx}-\frac{1}{3}L_{\cos 2nx}-\frac{2L^2_{\sin px}}{9L_{mx}}\right)i_{dx}\\ +\left(\frac{2L_{\sin px}L_{\cos px}}{9L_{mx}}-\frac{L_{\sin 2nx}}{3}\right)\frac{di_{dx}}{dt}+\omega\left(\frac{L_{\sin 2nx}}{3}-\frac{2L_{\sin px}L_{\cos px}}{9L_{mx}}\right)i_{qx}\\ =\tilde{e}_q-u_{qx}-\frac{2L_{\sin px}}{3L_{mx}}u_{zx}\end{cases} \quad (7)$$

In practical applications, the average distinction in filter inductance between its real value and nominal is regularly about ±10%, even under serious condition, the distinction could be restricted to a worthy range. In this way, by precluding the insignificant high-arrange terms in (7), the scientific model of active-reactive can be at long last acquired as:

$$\begin{cases}(L_{mx}+\frac{1}{3}L_{\cos 2nx})\frac{di_{dx}}{dt}-\omega(L_{mx}+\frac{1}{3}L_{\cos 2nx})i_{qx}\\ =\tilde{e}_d-u_d+\frac{L_{\sin 2n}}{3L_{mx}-L_{\cos 2nx}}(\tilde{e}_q-u_q)+\frac{2L_{\cos px}}{3L_{mx}-L_{\cos 2nx}}u_{zx}\\ (L_{mx}-\frac{1}{3}L_{\cos 2nx})\frac{di_{qx}}{dt}+\omega(L_{mx}-\frac{1}{3}L_{\cos 2nx})i_{dx}\\ =\frac{L_{\sin 2nx}}{3L_{mx}+L_{\cos 2nx}}(\tilde{e}_d-u_d)+\tilde{e}_q-u_q-\frac{2L_{\sin px}}{3L_{mx}-L_{\cos 2nx}}u_{zx}\end{cases} \quad (8)$$

Where L_{mx} is the normal estimation of three phase inductance , L_{cos2nx},L_{cospx} and L_{sin2nx} L_{sinpx} are the cosine and sine terms of the unbalanced filter inductance in parallel modules with 2ω and ω frequency, individually, While $\tilde{e}_d$, $\tilde{e}_q$ speak to the active and reactive components of unbalanced grid voltage in PSRF and u_{zx} is the zero-sequence segment in output voltage.

Define

$$Z_{dx}=(L_{mx}+\frac{1}{3}L_{\cos 2nx})p \ , \ Z_{qx}=(L_{mx}-\frac{1}{3}L_{\cos 2nx})p$$

Where *p* is the differential operator and

$$L_{qdx}=L_{mx}+\frac{1}{3}L_{\cos 2nx}, \ L_{dqx}=L_{mx}-\frac{1}{3}L_{\cos 2nx}, \ \lambda_{qdx}=\frac{L_{\sin 2n}}{3L_{mx}-L_{\cos 2nx}}$$

$$\lambda_{dqx}=\frac{L_{\sin 2nx}}{3L_{mx}+L_{\cos 2nx}}, \ \lambda_{zdx}=\frac{2L_{\cos px}}{3L_{mx}-L_{\cos 2nx}}, \ \lambda_{zqx}=\frac{2L_{\sin px}}{3L_{mx}-L_{\cos 2nx}}$$

as the coupling coefficients inside the active-reactive current system and between the active-reactive current system and ZSCC system. At that point the frame of active-reactive current system can be gotten as Fig.2.

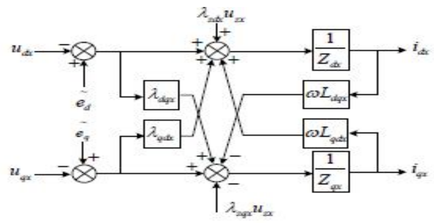


Fig.2. Active-reactive current system in PSRF under generalized unbalanced operating conditions

It is intriguing to take note of that the unbalance factors in filter inductance will lead oscillatory components with angular frequency of 2ω to the line impedance in PSRF. In addition, comparable oscillatory terms will likewise show up in grid voltage components $\tilde{e}_d$ $\tilde{e}_q$because of the presence of negative-sequence part in grid voltage. Moreover, when the well known SVPWM tweak strategy is received, the zero-sequence output voltage at ac side in the parallel modules will be a triangular voltage with a angular frequency of 3ω [29], and this consequently , will likewise create 2ω oscillatory segments in the active-reactive current system. Tragically, all these oscillatory terms will offer ascent to negative-sequence currents in parallel modules.

For the most part, the negative-sequence currents will bring about uneven output currents and cause diverse switching losses in three bridges of a single converter. Also, it will most likely reason negative-sequence segment in circuiting currents. As per the hypothesis delineated in [18], the negative-sequence circuiting current under summed up uneven working conditions can be communicated as:

$$i_{cn}=\frac{1}{6}\left[\begin{array}{l}\left(\frac{e_a-u_{NO}-d_{a1}u_{dc}}{Z_{a1}}+\alpha^2\frac{e_b-u_{NO}-d_{b1}u_{dc}}{Z_{b1}}+\alpha\frac{e_c-u_{NO}-d_{c1}u_{dc}}{Z_{c1}}\right)\\ -\left(\frac{e_a-u_{NO}-d_{a2}u_{dc}}{Z_{a2}}+\alpha^2\frac{e_b-u_{NO}-d_{b2}u_{dc}}{Z_{b2}}+\alpha\frac{e_c-u_{NO}-d_{c2}u_{dc}}{Z_{c2}}\right)\end{array}\right] \quad (9)$$

Where $\alpha=e^{j\frac{2\pi}{3}}$ is the fortes cue operator, $Z_{kx}=L_{kx}p(k=a,b,c;x=1,2)$ .As (9) shows, the negative-sequence circulating current can be repressed by smothering the negative-sequence segments in output currents or by disposing of their distinction. In practical applications, the earlier plan is regularly favored as it can viably take out the auxiliary impacts of negative-sequence currents.

B.Model of the ZSCC System

The ZSCC is a noteworthy worry for the converters in the parallel structure as it will twist the output currents and undermine the execution of the system. A normal model of the ZSCC system under summed up uneven working conditions will be great in dissecting the influencing factors of zero-sequence part and creating enhanced control calculation. From (6) one can see that the ZSCC system is combined with the active-reactive current system. Decoupling would be convoluted and not practical. To secure a legitimate numerical model for the zero-sequence system, assume both the active and reactive currents are all around well controlled with negative-sequence components killed. For this situation, both the varieties in active and reactive currents can be steady state. Therefore, ZSCC system can be rearranged as:

$$\begin{cases} -\frac{\omega L_{\sin p1}}{3} i_{d1} - \frac{\omega L_{\cos p1}}{3} i_{q1} + L_{m1} \frac{di_{z1}}{dt} = -u_{z1} \\ -\frac{\omega L_{\sin p2}}{3} i_{d2} - \frac{\omega L_{\cos p2}}{3} i_{q2} + L_{m2} \frac{di_{z2}}{dt} = -u_{z2} \end{cases} \quad (10)$$

For a two converter parallel system, there is only one ZSCC circulating through the modules, namely $i_{z1} + i_{z2} = 0$. Hence the average model of ZSCC system can be obtained as:

$$(L_{m1} + L_{m2}) \frac{di_{z2}}{dt} = u_{Lz1} - u_{Lz2} + u_{z1} - u_{z2} \quad (11)$$

Where u_{Lzx} can be calculated as:

$$u_{Lzx} = -\frac{\omega i_{dx} L_{\sin px}}{3} - \frac{\omega i_{qx} L_{\cos px}}{3}$$
$$= \begin{bmatrix} \omega L_{ax} & \omega L_{bx} & \omega L_{cx} \end{bmatrix} \begin{bmatrix} -\sin \omega t & -\cos \omega t \\ -\sin(\omega t - \frac{2}{3}\pi) & -\cos(\omega t - \frac{2}{3}\pi) \\ -\sin(\omega t + \frac{2}{3}\pi) & -\cos(\omega t + \frac{2}{3}\pi) \end{bmatrix} \begin{bmatrix} i_{dx} \\ i_{qx} \end{bmatrix} \quad (12)$$

As can be observed, u_{Lzx} is the zero-sequence voltage drop on the filter inductance, integrally. Define $\Delta u_{Lz} = u_{Lz1} - u_{Lz2}$ as the difference in inductance zero-sequence voltages between parallel modules and $\Delta d_z = d_{z1} - d_{z2}$ as the zero-sequence duty ratio difference, then the average model of ZSCC system can be calculated as:

$$(L_{m1} + L_{m2}) \frac{d_{iz2}}{dt} = \Delta u_{Lz} + \Delta d_z u_{dc} \quad (13)$$

As can be seen, the unbalance factors in filter inductance will additionally add to creating ZSCC.

III. PROPOSED CONTROL SCHEME FOR PARALLEL SYSTEMS UNDER GENERALIZED UNBALANCED OPERATING CONDITIONS

A. Control of Negative-sequence Circulating Current

To inhibit the negative-sequence circulating current, endeavors ought to be made to suppress the negative-sequence components. Routinely, a PI controller can be embraced in PSRF to control the active and reactive currents gave that the filter inductance and grid voltage are balanced. Be that as it may, from the previously mentioned, it emerges that both the unbalance factors in filter inductance and grid voltage will offer ascent to creating negative-sequence components in the output currents and this negative-sequence part would most likely outcome in unbalanced output currents and much more genuinely, negative-sequence circulating current between the parallel modules. Tragically, since a negative-sequence part shows up as 2ω ac segment in PSRF, the PI controller is definitely not ready to smother it without steady state error. To smother the negative-sequence currents, a resonant controller can be fortified to the traditional PI controller. The fortified PI controller (we refer to PIR controller) can be communicated as:

$$G_c(s) = k_p + \frac{k_i}{s} + \frac{k_r s}{s^2 + \omega_r s / Q + \omega_r^2} \quad (14)$$

Where k_p, k_i and k_r are the proportional, integral, and resonant gain pick up parameters of the PIR controller, individually, and $\omega_r = 2\omega$ is the resonant frequency of the controller while Q can be characterized as the quality factor of the controller. The resonant capacity of $G_c(s)$ can give a moderately extensive pick up to the negative-sequence currents of 2ω frequency in PSRF with a large Q. And it is this large gain vast pick up that will successfully smother the negative-sequence components in the active and reactive currents in steady state. With respect to the positive-sequence part in active and reactive currents, which is for all intents and purposes dc part, the PI capacity of $G_c(s)$ will oversee it with nearly zero error in steady state.

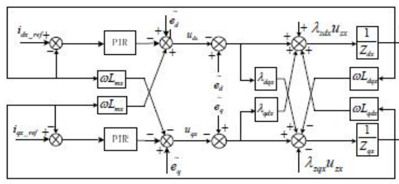


Fig.3. control block diagram of the active and reactive current system PSRF

The control piece frame of active-reactive current system is shown in Fig.3, and the outputs of current controllers can be computed as:

$$\begin{cases} u_{dx} = -(k_p + \frac{k_i}{s} + \frac{k_r s}{s^2 + \omega_r s/Q + \omega_r^2})(i_{dx\_ref} - i_{dx}) + \omega L_{mx} i_{qx} + \tilde{e}_d \\ u_{qx} = -(k_p + \frac{k_i}{s} + \frac{k_r s}{s^2 + \omega_r s/Q + \omega_r^2})(i_{qx\_ref} - i_{qx}) - \omega L_{mx} i_{dx} + \tilde{e}_q \end{cases} \quad (15)$$

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

Control of ZSCC with SVPWM Modulation Technique

The SVPWM modulation system is connected in the control of three-phase PWM converters because of its propelled highlights counting high dc voltage utilization and less distortions in converter output currents. The control vector v_s in each PWM cycle, as showed in Fig.4, is orchestrated by two contiguous non-zero vectors V_i (i=1, 2, 3, 4, 5, 6) and two zero vectors V_j (j=0, 7). A regular vector circulation of this balance system when V_s lies between V_4 and V_6 is delineated in Fig.5, where T_s is the time span of a PWM cycle, and d_1 , d_2 speak to the duty ratios of the two nonzero vectors. The two zero vectors are uniformly disturbed toward the starting end and center of a PWM cycle and their aggregate duty ratio can be computed $d_0 = 1 - d_1 - d_2$. Another preferred standpoint of this tweak method lies in that the length of two zero vectors can be redistributed and this propelled highlight can be utilized to suppress the ZSCC.

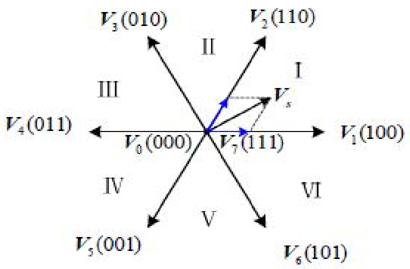


Fig.4. the synthesis of control voltage vector with basic voltage vectors

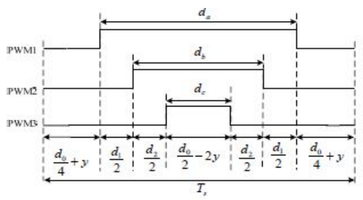


Fig.5. Distribution of vectors with zero-vector correction variable adopted

As (13) shows, the ZSCC can be suppressed by regulating the zero-sequence duty ratios of parallel modules. A control variable y can be acquainted with direct the span of zero vectors V_0 and V_7 , as appeared in Fig. 5. The presented control variable will redistribute the zero vectors in a PWM cycle, yet would not influence the distinctions in phase duty ratios

Subsequently, the execution of active-reactive current sequence of every individual converter won't be influenced. Be that as it may, as can be noticed, the zero-sequence duty ratio can be suited as:

$$\begin{aligned} d_{zx} &= (d_{ax} + d_{bx} + d_{cx})/3 \\ &= ((d_{1x} + d_{2x} + d_{0x}/2 - y_x) + (d_{2x} + d_{0x}/2 - y_x) + (d_{0x}/2 - y_x))/3 \\ &= (3/2 - d_{1x}/2 + d_{2x}/2 - 6y_x)/3 \end{aligned} \quad (16)$$

Where d_{1x} and d_{2x} (x=1, 2) speak to the two nonzero vectors of the parallel modules. In a two converter parallel system, as it were one ZSCC exists. In this manner, by smothering the ZSCC in one of the parallel modules, the zero-sequence segment in output currents can be adequately wiped out consequently. Pick converter 2 as the objective with control variable y_2, and converter 1 embraces the traditional SVPWM modulation procedure, i.e $y_1 = 0$ At that point the normal model of the ZSCC can be

$$\frac{di_{z2}}{dt} = \frac{\Delta u_{Lz} + (\Delta d_{12}/12 + y_2) \cdot 2u_{dc}}{(L_{m1} + L_{m2})} \quad (17)$$

Where $\Delta d_{12} = (d_{21} - d_{11}) - (d_{22} - d_{12})$ is the difference in nonzero vectors duty ratios. Neglect the fluctuation in dc bus voltage, the Laplace transform of (17) can be obtained as:

$$I_{z2}(s) = \frac{\Delta U_{Lz} + (\Delta D_{12}/12 + Y_2)2U_{dc}}{s(L_{m1} + L_{m2})} \quad (18)$$

Where ΔU_{Lz} , ΔD_{12} and Y_2 are the Laplace transform of Δu_{Lz} , Δd_{12} and y_2 individually. At that point the ZSCC system can be portrayed as Fig.6. Ordinarily, in the measured framed

Converters, the unbalance factors in filter are frequently overlooked. In this way, the outputs of active-reactive current controllers in (15) are roughly equivalent. Therefore, the effects of Δd_{12} and Δu_{Lz} can be disregarded. At that point the normal model of ZSCC can be rearranged as:

$$I_{z2}(s) = \frac{2Y_2 U_{dc}}{s(L_{m1}+L_{m2})} \quad (19)$$

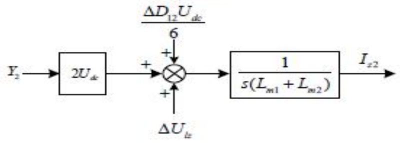


Fig.6. ZSCC system under generalized unbalanced operating conditions

As (19) shows, in a perfect world the ZSCC loop of the modular designed parallel system is a first order system autonomous of the active-reactive current system. Perceiving this property, a basic PI controller can be utilized to suppress the circulating current, and the output of the zero-axis current controller can be acquired as:

$$y_2 = (k_{pz} + \frac{k_{iz}}{s})(i_{z2\_ref} - i_{z2}) \quad (20)$$

Where i_{z2_ref} is the reference value of ZSCC, and k_{pz} , k_{iz} the parameters of the circulating current PI controller.

A. Control of ZSCC with Improved Feed-forward Method

Theoretically, when the parallel modules share the same value in balanced filter inductance, the effects of Δu_{Lz} and Δd_{12} can be ignored and relatively satisfactorily circulating current concealment execution can be accomplished with the traditional PI strategy. Notwithstanding, in handy applications, tolerance in inductance estimations of up to $\pm 10\%$ is very normal, which would add to unbalance in filter inductance. Shockingly, as per (15), the unbalance factors in filter inductance will consequently offer ascent to various output ac voltages for the parallel converters. Also, as (12) shows, different inductance zero-sequence voltages will most likely be delivered. In view of the investigation previously mentioned the angular frequency of Δu_{Lz} is ω , simply the angular frequency of grid integral segment, which is generally lower than the bandwidth of ZSCC control system. In a word, as delineated in Fig.7, both Δu_{Lz} and Δd_{12} will make significant disturbances the ZSCC system. Thusly, the smothering performance of PI controller would be disintegrated.

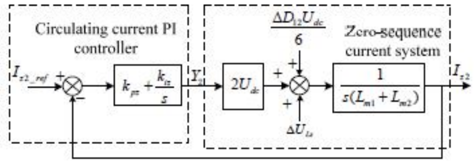


Fig.7. Zero-sequence current loop with filter inductance unbalanced

To defeat the disadvantage of traditional PI technique in smothering ZSCC and eliminate the effects caused by Δu_{Lz} and Δd_{12} , feed-forward procedure on the premise of traditional PI strategy is proposed as appeared in Fig.8.The feed forward quantity $\Delta d_{12}/12$ and $\Delta u_{Lz}/2u_{dc}$ are utilized to dismiss the disturbances caused by Δd_{12} and Δu_{Lz} individually. With the proposed feed-forward control procedure, the circuiting current control variable can be gotten as:

$$y_2 = (k_{pz} + \frac{k_{iz}}{s})(i_{z2\_ref} - i_{z2}) - \frac{\Delta d_{12}}{12} - \frac{\Delta u_{lz}}{2u_{dc}} \quad (21)$$

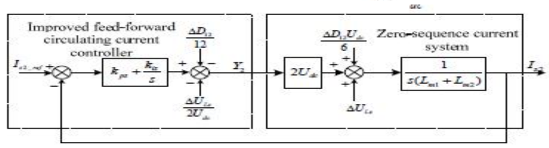


Fig. 8 Improved feed-forward circulating current control strategy

Theoretically, the disturbances in ZSCC system can be successfully rejected and better concealment execution can be accomplished.

The system control piece frame of the proposed control plot for the parallel system is appeared in Fig.9. The active and reactive currents are controlled by PIR controllers which can successfully repress the negative-sequence components in output currents and suppress the negative-sequence circulating current. It ought to be noticed that the outputs $u_{\alpha x\_ref}$ and $u_{\beta x\_ref}$ are the Clarke transformation of u_{dx} and u_{qx} individually. Furthermore, it is worth saying that a notch filter is utilized as a part of the Phase Locked Loop (PLL) to follow the phase angle of positive-sequence part in the grid voltage. The transfer function of the notch filter is:

$$F(s) = \frac{s^2 + \omega_n^2}{s^2 + \omega_n/Q_f + \omega_n^2} \quad (22)$$

Where $\omega_n = 2\omega$
($\omega$is the grid fundamental angular frequency) and Q_f=10

The ZSCC control piece is shown in the shaded area. The ZSCC in converter 2 is suppressed to take out the zero-sequence component in output currents of the parallel modules. The contrast between i_{2z} and its reference value is fed into the PI controller. In the feed-forward quantity of Δd_{12} is acquired by figuring the time duration of two Non zero vectors $t_{1x} and\ t_{2x} (x = 1,2)$ in each PWM cycle as $d_{1x} = \frac{t_{1x}}{T_s}, d_{2x} = t_{2x}/T_c$ At the same time, condition (12) is used to get another feed- forward quantity $\Delta u_{lz}/2u_{dc}$ At that point the ZSCC control variable y_2 is used to modify the zero-sequence duty ratio of converter 2 by redistributing the time duration of zero vectors in each PWM cycle.

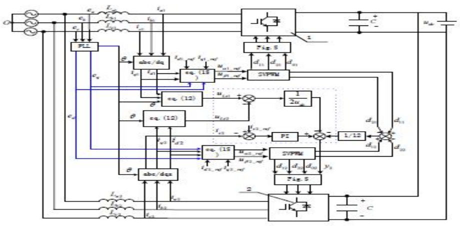


Fig. 9 System block diagram of the parallel three phase PWM structure with Improved feed-forward circulating current controller

B. Control of ZSCC with PIR Method

Since the disturbances in ZSCC system caused by unbalance factors in filter inductance ought to be figured in encourage forward technique, so the enhanced feed-forward circuiting current controller is sensitive to parameters of filter inductances.

From condition (12), the unsettling influences caused by unbalance filter inductances can be communicated:

$$\Delta u_{lzx} = -\omega i_d(\Delta L_a \sin\omega t + \Delta L_b \sin(\omega t - 2\pi/3) + \Delta L_c \sin(\omega t + 2\pi/3)) - \omega i_q(\Delta L_a \cos\omega + \Delta L_b \cos(\omega t - 2\pi/3) + \Delta L_c \cos(\omega t + 2\pi/3)) \quad (23)$$

where $\Delta L_a = L_{a1} - L_{a2}$, $\Delta L_b = L_{b1} - L_{b2}$, $\Delta L_c = L_{c1} - L_{c2}$.

In steady state, the currents in dq frame are consistent, so it can be seen that the unsettling influences caused by unbalance filter inductances is the variance in grid frequency. So the transformation in grid frequency can be smothered by resonance controller. In view of the technique in [26], the ZSCC controller is as per the following:

$$y_2 = \left(k_{pz} + \frac{k_{iz}}{s} + \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2}\right)(i_{z2\_ref} - i_{z2}) - \frac{\Delta d_{12}}{12} \quad (24)$$

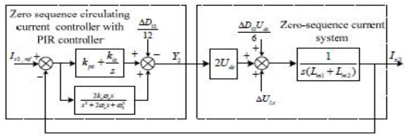


Fig. 10 Proposed Circulating Current Control Strategy with PIR controller

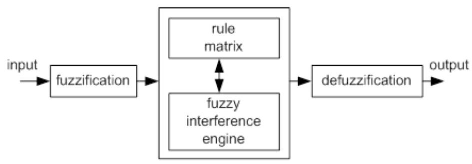
The both proposed plan can be connected to three-phase PWM converter parallel system which contains communication line .Though Communication synchronization and the accurate information of filter inductance in parallel modules are the key factors in ensuring the circulating current in suppression performance.

Extension:

FUZZY LOGIC

Fuzzy rationale is a type of numerous esteemed rationales in which reality estimations of variables might be any genuine number somewhere around 0 and 1. By differentiation,, in Boolean rationale, reality estimations of factors may simply be 0 or 1.Fuzzy rationale has been extended to deal with the possibility of halfway truth, where reality quality may stretch out between totally genuine and totally false. In addition, when etymological factors are used, these degrees may be supervised by specific limits.

Normally fuzzy rationale control system is produced using four significant segments displayed on Figure fuzzification interface, fuzzy induction motor, fuzzy logical structure and defuzzification interface. Each part nearby essential fuzzy rationale operations will be depicted in more detail below



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The fuzzy rationale investigation and control systems showed up in Figure 1 can be depicted as:

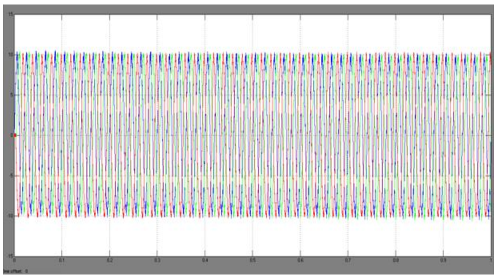
1. Receiving one or extensive number of estimations or other evaluation of conditions existing in some system that will be dismembered or controlled.
2. Processing all got inputs as indicated by human based, fuzzy "expecting then" norms, which can be conveyed in

fundamental dialect words, and combined with routine non-fuzzy get ready.

3. Averaging and weighting the results from all the individual standards into one single output decision or sign which picks what to do or advises a controlled system what to do. The result output sign is a correct defuzzified esteem. Above all else, the distinctive level of yield (fast, low speed and so on.) of the stage is characterized by determining the enrollment capacities for the fluffy sets.

SIMULATION RESULTS

Parallel case1



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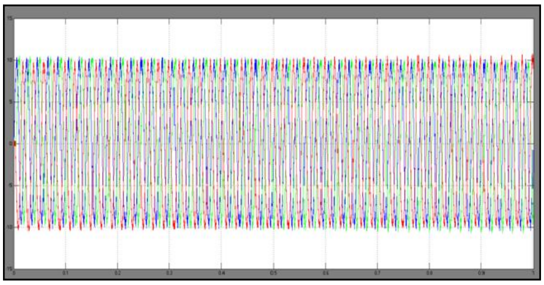

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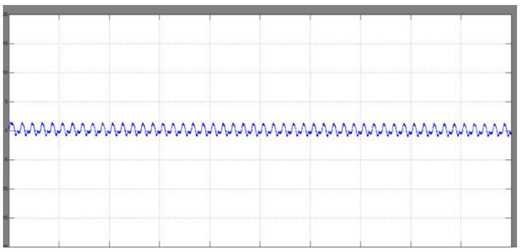

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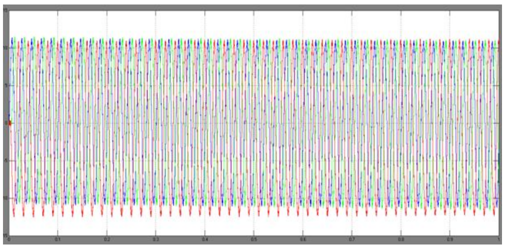
Parallel case2



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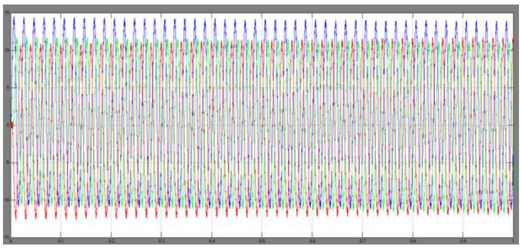

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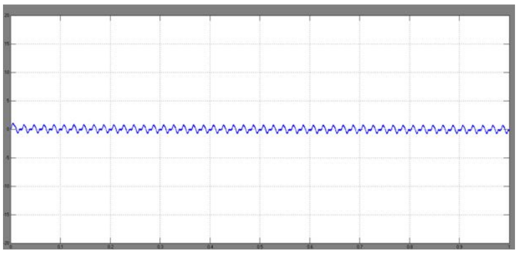

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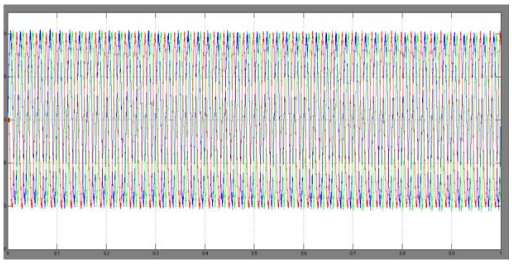
Parallel case 13



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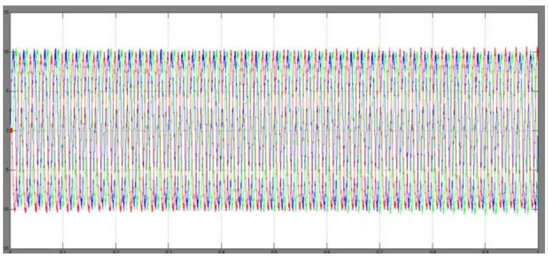

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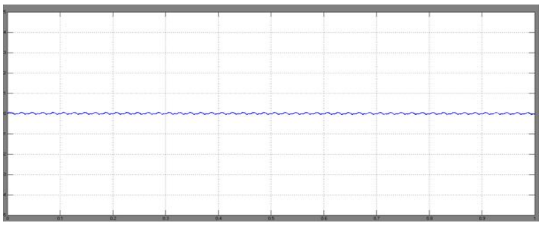

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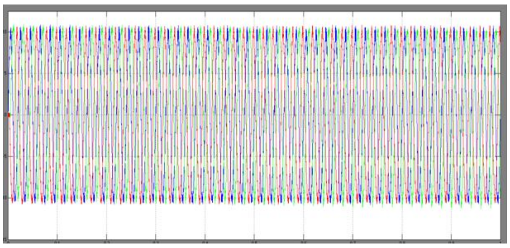
Parallel case13 unbalanced



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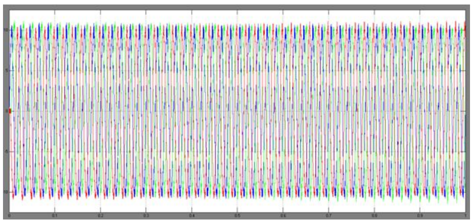

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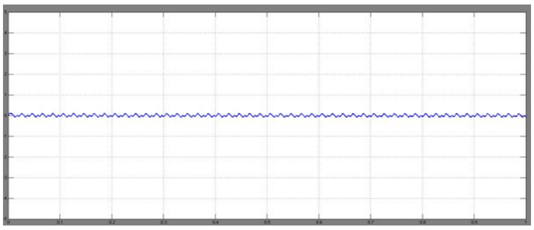

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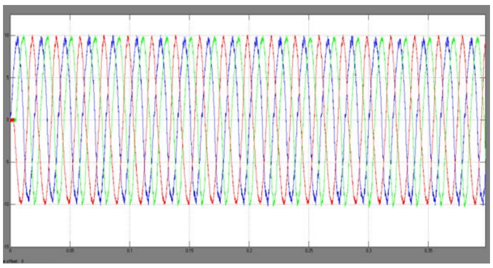
Parallel case14



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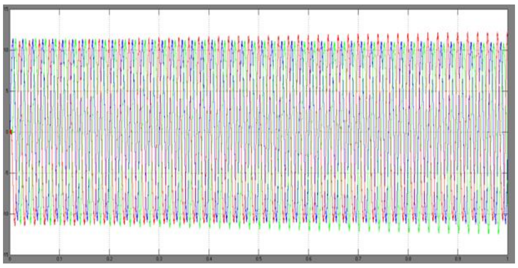

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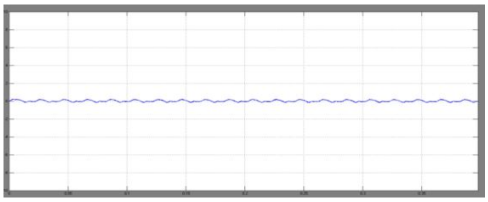

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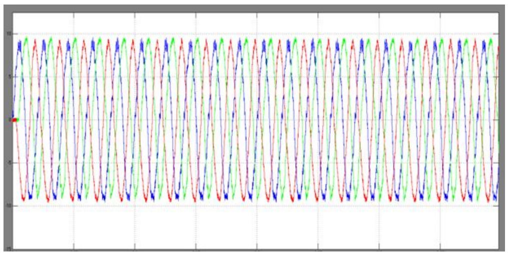
Parallel case14 unbalanced



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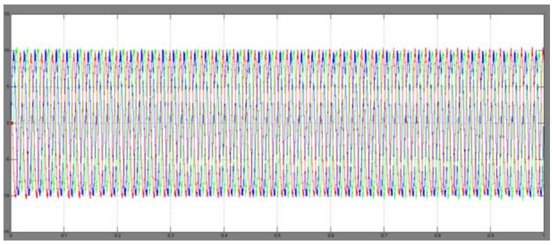

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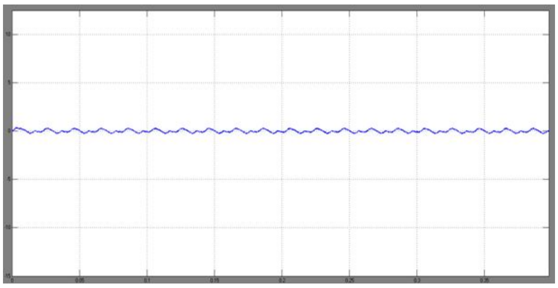

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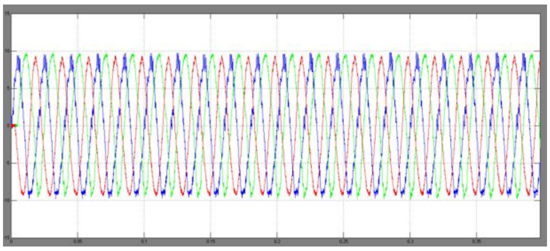
Parallel case15_1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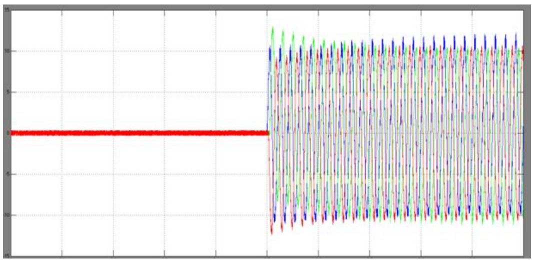
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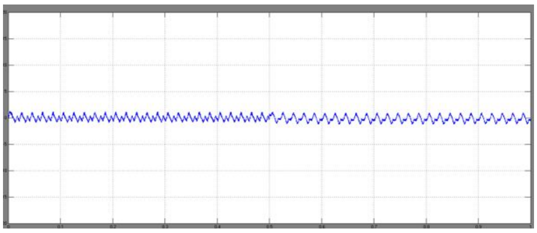
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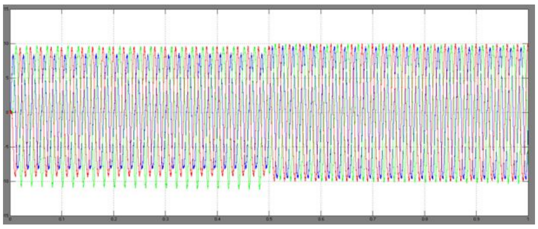
Parallel case 15_2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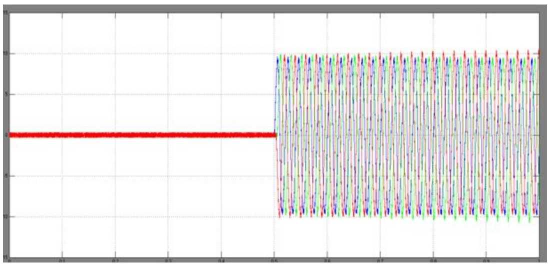
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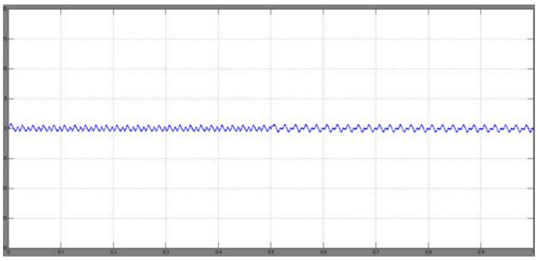
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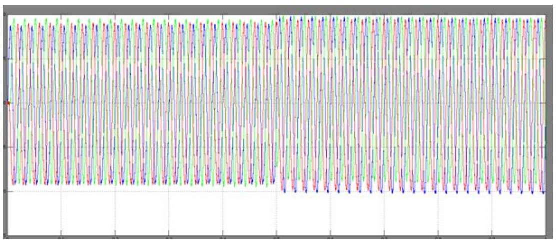
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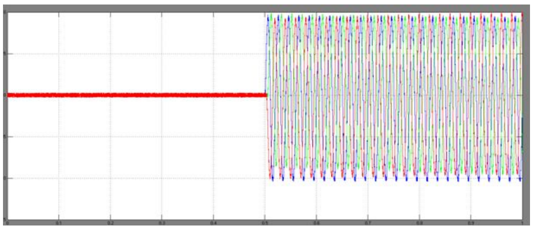
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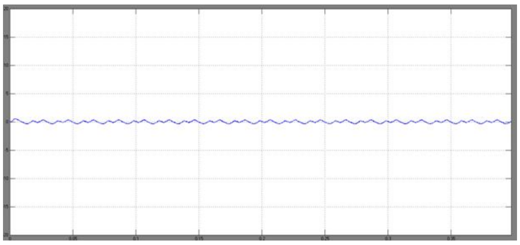
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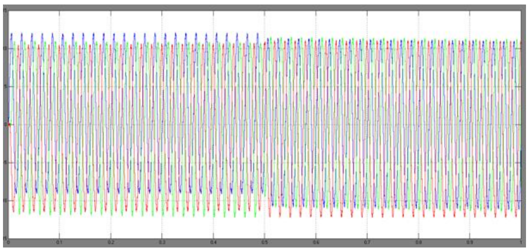

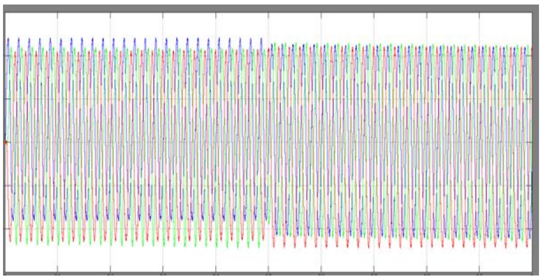

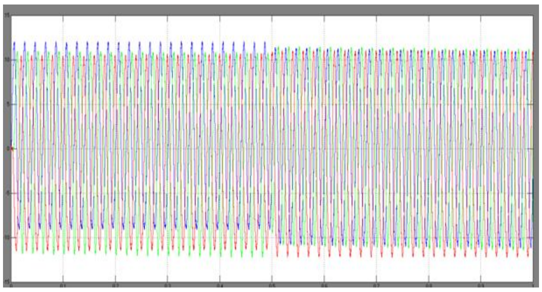

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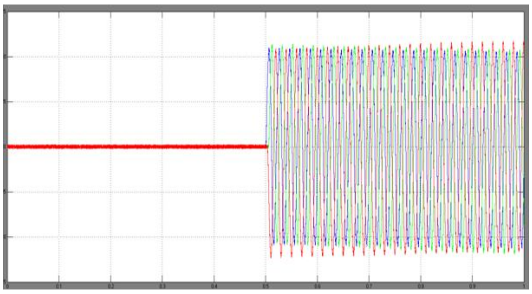

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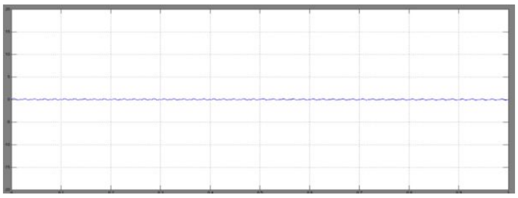

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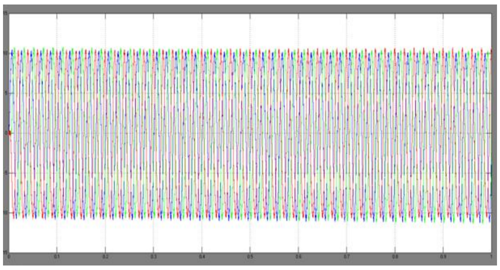
Parallel case 33



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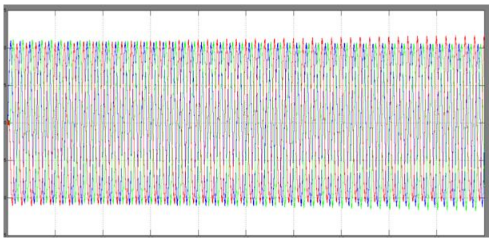

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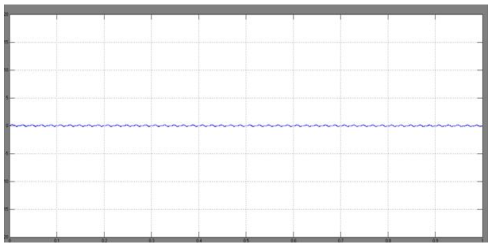

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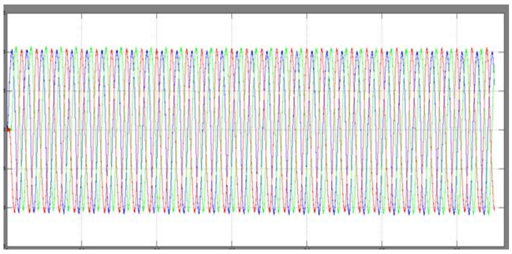
Parallel case14



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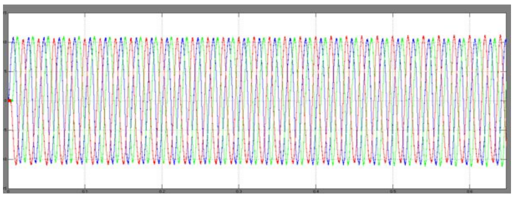

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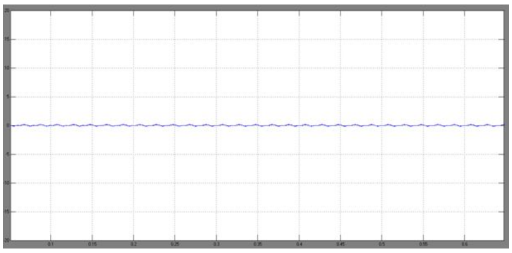

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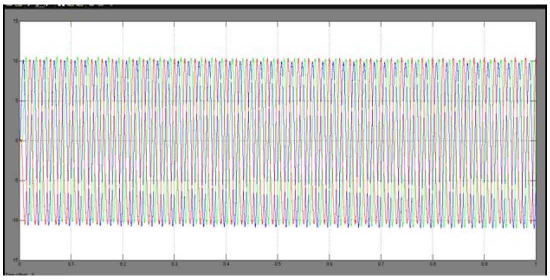
Extension

Parallel Case



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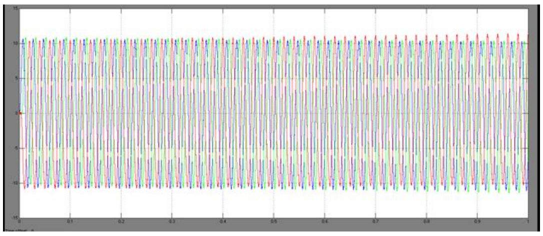

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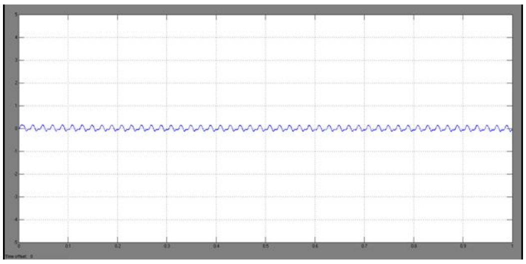

3Iz1

IV. CONCLUSION

This paper has proposed another plan to control parallel three phase PWM converters under summed up uneven conditions. The unbalance factors in filter inductance will give rise to negative-sequence components in output currents and make unsettling influences the ZSCC system. Subsequently, circulating currents would be created and the output currents and flows of parallel modules would be twisted. By stifling the negative-sequence components in output currents, the Negative - sequence circulating current can be adequately repressed. In addition, the disturbances in ZSCC system can be successfully dismisses by the proposed feed-forward technique or PIR controller. Enhanced circuiting currents concealment execution can be accomplished, and subsequently, the contortions in output currents of parallel modules could be extraordinarily decreased. Experimental results validate the performance and effectiveness of the proposed scheme.

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