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Applying a Control Strategy Consisting of TCCF in Four-Leg Shunt Active Filter in Order to Improve Power Quality

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***Abstract*—In this paper, a control scheme is proposed to compensate nonlinear and unbalanced loads currents and mitigate neutral current in a weak distribution network utilizing a four-leg converter. Two separate Complex Coefficient-Filters (CCF) have been used to extract the fundamental frequency positive sequence component of the load current and the converter to compensate for and control the dc- link voltage. Also, due to the presence of unbalance and harmonics the voltage of the weak grid, a CCF-based Phase Locked Loop (PLL) has been used for proper synchronization with grid voltage. Owing to absence of a low-pass filter in the CCF structure does not reduce the system dynamics and increases the speed and accuracy of estimation of the frequency and phase angle of the grid voltage. The Triple-CCF (TCCF) control strategy proposed in this article is compared with the same case, Triple-Reduced Order Generalized Integrator (TROGI). Simulation results show the performance and efficiency of the four-leg active filter control strategy based on TCCF.**

Keywords— Triple- Complex Coefficient-Filters, Four-Leg Converter, Active Power Filter, Power Quality.

I. INTRODUCTION

In four-wire three-phase distribution systems in the presence of a balanced and harmonic-free grid, the use of a four-wire inverter as an active filter plays a key role in compensating nonlinear and unbalanced loads[1],[2].

In controls strategies for grid-connected inverters, it is important to synchronize fundamental components with the grid voltage, and this is the responsibility of a Phase Locked Loop (PLL). On the other hand, synchronization of other components with the grid voltage is a major challenge in such research; as the phase, amplitude and frequency of the grid voltage are essential information for the adequate performance of grid-connected inverter control systems. In such applications, exact and apace detection of phase angle, amplitude, and frequency is essential to ensuring proper production of reference signals and compliance with standards [3].

Researchers have been exploring ways to improve the disturbance rejection capability of conventional Synchronous Reference Frame-PLL (SRF-PLL). It has been found that increasing PLL bandwidth leads to an increase in phase-frequency coupling, causing large transients in the estimated frequency at the time of starting and phase-angle jumps. Additionally, increasing the bandwidth of SRF-PLL reduces its noise immunity [4], [5].

So as to increase the filtering capability of SRF-PLLs, the Delayed Signal Cancellation (DSC) operator has been used as an internal filter of the loop or before the SRF-PLL input. The DSC has been more used in the control structures of modern day converters before the SRF-PLL input; this is because its use increases the phase delay within the loop, but the dynamic response of the PLL is slowed down. Also, such strategies have a good performance in their nominal frequency, and in the case frequency deflection from its nominal quantity, their disturbance rejection selectivity will be impaired[6],[7].

In [8], Reduced Order Generalized Integrator-PLL (ROGI-PLL) is investigated and in both grid frequency deviation and unbalanced grid voltage condition, the dynamic performance of this type of PLL is specified. Thanks to absence of a low-pass filter in the ROGI-PLL structure, its dynamic performance is relatively favorable and the Fundamental Frequency Positive Sequence Components(FFPSC) of the grid voltage in less than 2.5 cycles have been detected in the test (grid frequency deviation). In [9], the Multiple Complex Coefficient Filter-Frequency Locked Loop (MCCF-FLL) technique for different voltage modes is investigated. In CCF technique, without the need for symmetrical component method or many complex rotating frame transformations, the information of harmonic and fundamental components of voltage can be obtained with great speed and accuracy under distorted and unbalanced grid which will be useful in active filter control strategy.

To overcome the drawbacks of methods mentioned above, a novel control algorithm namely TCCF combined with multi-PR controller is proposed in this paper. The Triple-CCF (TCCF) technique is used for the control strategy of the four-leg active filter (Figure 1) in the presence of a weak distribution network. That is to say, this method is suitable for use in Microgrids (MGs), which are weak networks, and MGs are also an important part of smart grids [10]. For this purpose, two CCF blocks have been used to extract fundamental components of compensation and dc link voltage control in order to perform the required reference currents for active filter. The third block of CCF is used to extract the fundamental components of grid voltage that have

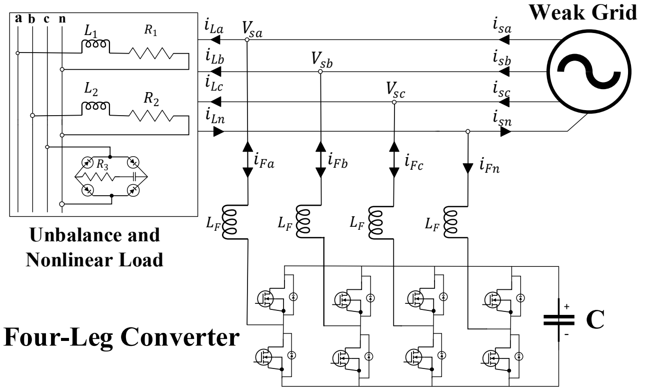


Fig. 1. The structure of the four-leg active filter in the presence of a weak grid and unbalanced and nonlinear load.

harmonics and imbalances. The performance of ROGI and CCF based PLLs has been thoroughly investigated and tested under grid frequency deviation and unbalanced grid voltage condition and the better performance of CCF-PLL is show. Simulation results show that the grid current compensation with the TCCF strategy is properly achieved and the grid current THD is less than 2%.

II. PROPOSED CONTROL STRATEGY

A. Complex Coefficient-Filter

The feature of comprehensive integrators such as CCF is not just to keep unity gain and zero phase shift at a specified frequency and not to reject other frequencies; it also provides fast response for real-time signal extraction. The CCF transfer function for the positive sequence at frequency $n\omega_0$ is Eq. (1). It can be seen from the transfer function that, its components are extracted for the frequency $+n\omega_0$ and for the frequencies $-n\omega_0$ and other frequencies, this transfer function behaves like a notch filter [11]:

$$CCF(s) = \frac{\omega_r}{s - jn\omega_0 + \omega_r} \tag{1}$$

where ω_r is the bandwidth of the filter. The CCF structure for extracting the fundamental and harmonic components of grid voltage and current, as shown in Fig. 2. This structure has been used to apace and accurately obtain the positive and negative sequence components [11]. This aspect is used in the next section to surmise the phase angle and frequency of the weak grid voltage.

B. TCCF Control Strategy

Fig. 3 shows the TCCF control strategy. In this strategy, using the concept of previous studies in CCF (Fig. 3), two CCF blocks are used to pull out the fundamental frequency of the positive components of load current and converter currents and these currents are used to calculate the power required that exchange between grid and converter. For the correct operation of the converter in the compensation mode and dc link voltage control mode, the grid is obliged to transfer the positive sequence active power to the converter, and on the other hand, the converter transfers remaining powers to the grid. The reference currents for the two modes of dc-link voltage control and compensation are in the form of relations (2) and (3):

$$\begin{cases} i^*_{ca+} = i^*_{sm+} \sin\left(\omega t + \theta^+_{v1}\right) \\ i^*_{cb+} = i^*_{sm+} \sin\left(\omega t - 2\dfrac{\pi}{3} + \theta^+_{v1}\right) \\ i^*_{cc+} = i^*_{sm+} \sin\left(\omega t + 2\dfrac{\pi}{3} + \theta^+_{v1}\right) \end{cases} \qquad (2$$

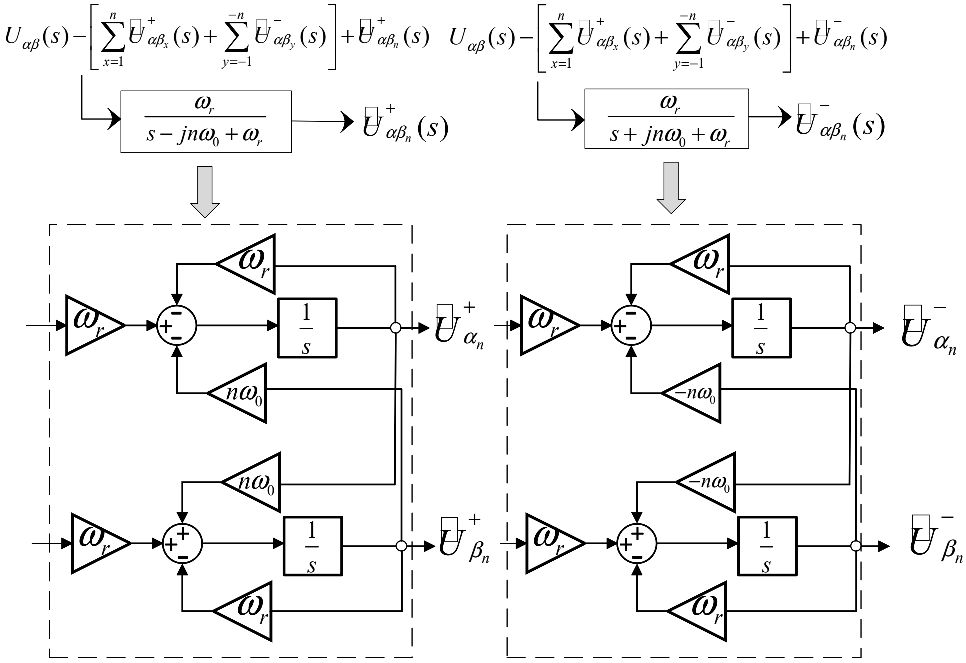


Fig. 2. Extraction of positive and negative sequence components by CCF [11]

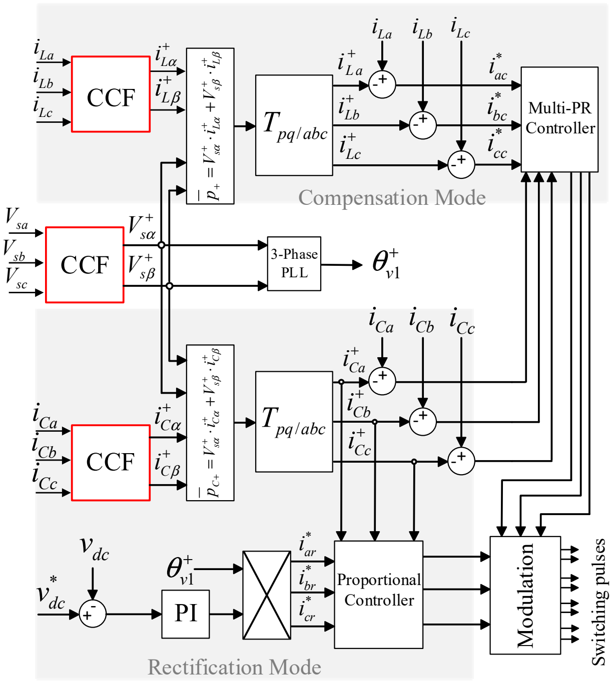


Fig. 3. TCCF control strategy

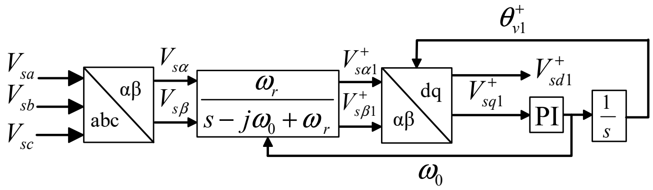


Fig. 4. CCF based PLL

$$\begin{bmatrix} i_{ac}^* \\ i_{bc}^* \\ i_{cc}^* \end{bmatrix} = \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} - \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \frac{1}{v_{s\alpha+}^2 + v_{s\beta+}^2} \begin{bmatrix} v_{s\alpha+} & -v_{s\beta+} \\ v_{s\beta+} & v_{s\alpha+} \end{bmatrix} \begin{bmatrix} \bar{p}_+ \\ 0 \end{bmatrix}$$

(3)

In equation (2), i_{ca+}^*, i_{cb+}^* and i_{cc+}^* are the reference currents of phases a, b and c for the dc link voltage control mode and i_{sm+}^* is the amplitude of reference positive sequence active power current that will be obtained from the PI controller. In equation (3),i_{ac}^* ,i_{bc}^* and i_{cc}^* are three-phase reference currents for compensation mode.

Under weak grid, accuracy in synchronizing fundamental components with grid voltage is of great importance. A CCF block (third CCF block) is used to elicit the fundamental frequency positive component of the source voltage to be used as a PLL input and the phase angle (θ_{v1}^+) and the fundamental frequency (ω_1^+) of the grid voltage can be achieved. For this purpose, a CCF tuned to the frequency ω_0 is used to obtain the fundamental component of the source voltage (Figure (4) shows the structure of the CCF-PLL). In this type of PLL, due to the absence of low-pass filters, the desired phase angle is calculated more quickly and its dynamic performance will be higher in frequency detection [11].

Among other TCCF strategy objectives is the reduction of the neutral wire current. Initially, zero sequence current are not considered and the calculations are carried out with this assumption. At the end of the control steps and for the fourth leg modulation signal, the converter is acted as Eq. (4) [1]:

$$m_n = -\left(m_a + m_b + m_c\right) \quad (4)$$

where m_a, m_b and m_c are the modulation signals for three-phase legs, respectively.

III. SIMULATION RESULTS

To assess the execution of the proposed control strategy, a simulation of this control strategy for a four-leg converter in the presence of a weak grid in the MATLAB/SIMULINK was presented and its performance was compared with the TROGI control strategy. First, to clarify the better performance of CCF-PLL and ROGI-PLL, these two PLLs have been tested in two modes: grid frequency deviation and unbalanced grid voltage condition. The parameters of the system is given in Table I.

A. *Compare Performance Of ROGI-PLL and CCF-PLL*

Case 1: Unbalanced Grid Voltage Condition: During system operation and at time t = 1.168s, RMS value of phase b voltage is reduced from 110v to 90v. The simulation results show that the CCF-PLL has a smaller settling time (10.977ms) than the ROGI-PLL (11.281ms) and detects the voltage value faster (Fig. 5).

Case 2: Grid Frequency Deviation: In this case, the grid frequency jumps to 55Hz at t = 1.168s. Fig .6 shows the performance of ROGI-PLL and CCF-PLL in tracking frequency and estimating phase angle during this change. As shown in Fig. 6, CCF-PLL has a faster dynamic response in frequency detection than ROGI-PLL.

B. *Simulation Results under Polluted Grid Voltage Condition*

The system of Fig. 1 is examined in the presence of a weak grid. Voltage source is defined as follows:

- including harmonics of the order of 5 and amplitude of 10% of the sinusoidal voltage.
- zero sequence components 20% of positive sequence component.

The four-leg converter in Fig. 1 under the TCCF control strategy, compensates the unbalanced and distorted current of the grid and the THD of the grid current for all three phases has reached the standard value. Among other strategy objectives is the reduction of the neutral wire current. As shown in Fig. 7(b), this value is almost zero.

The results of Fig. 7 show that the converter under the TCCF control strategy has a good performance in the compensation mode in the attendance of unbalanced and harmonic load and source. In dc-link voltage control mode, the converter under this strategy has kept the dc-link voltage fixed at its reference value

(320v), which indicates the good performance of this strategy in this mode (Fig. 7(d)).

Fig. 8 shows the THD value of phase c current before and after compensation. Phase c current has the highest THD current due to the attendance of single-phase diode bridge load in it, which after compensation with TCCF strategy, the THD current in that phase has reached less than 2% and found well within IEEE-519 standard limits (which has reached 2.74% with the TROGI strategy).

TABLE I. PARAMETERS OF SYSTEM

Parameters	**Value**
dc-link voltage (V_{dc})	320v
dc-link capacitor (C)	3600μF
Grid Voltage(V_s)	110V
Grid Frequency(f)	60Hz
Switching Frequency(f_s)	20KHz
Filter Inductor(L_F)	6mH
Phase A Load	$L_1 = 6mH\ , R_1 = 30\Omega$
Phase B Load	$L_2 = 6mH\ , R_2 = 27.5\Omega$
Phase C Load	$diode\ bridge(R_3 = 40\Omega)$

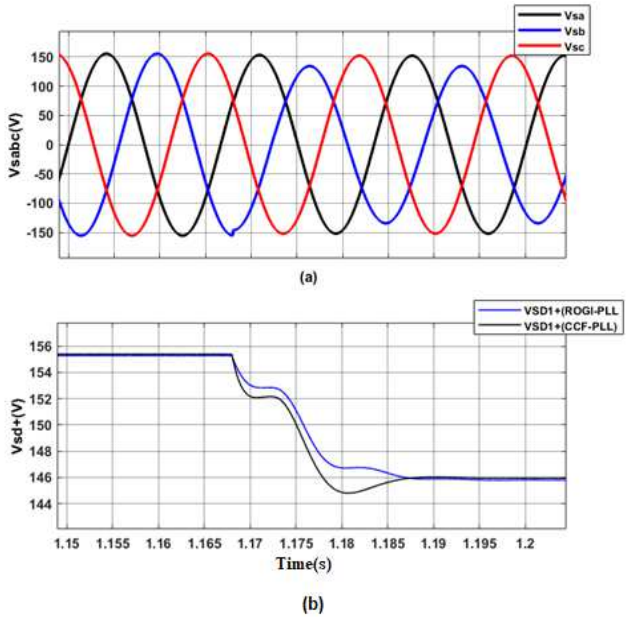


Fig. 5. (a):Three-phase voltage (b): d-axis voltage

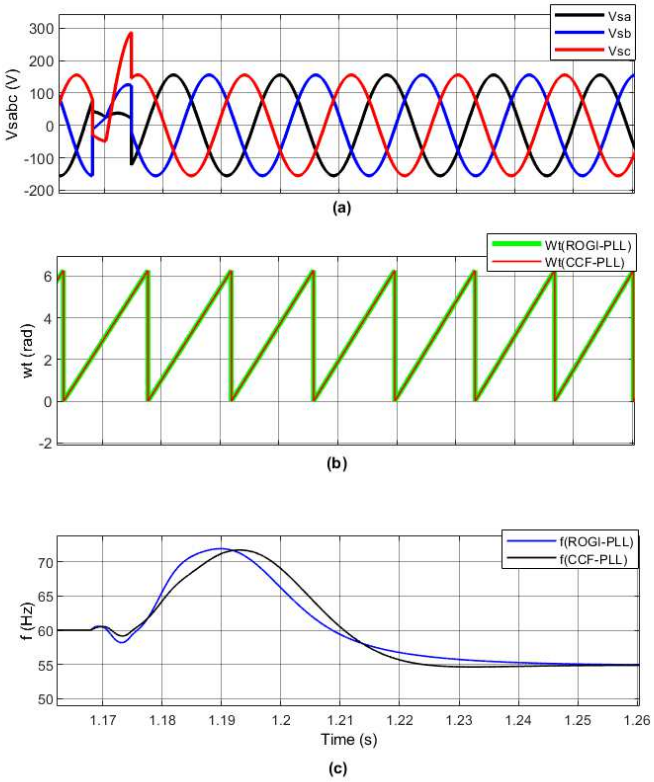


Fig. 6. (a):Three-phase voltage (b): Phase angle (c): frequency

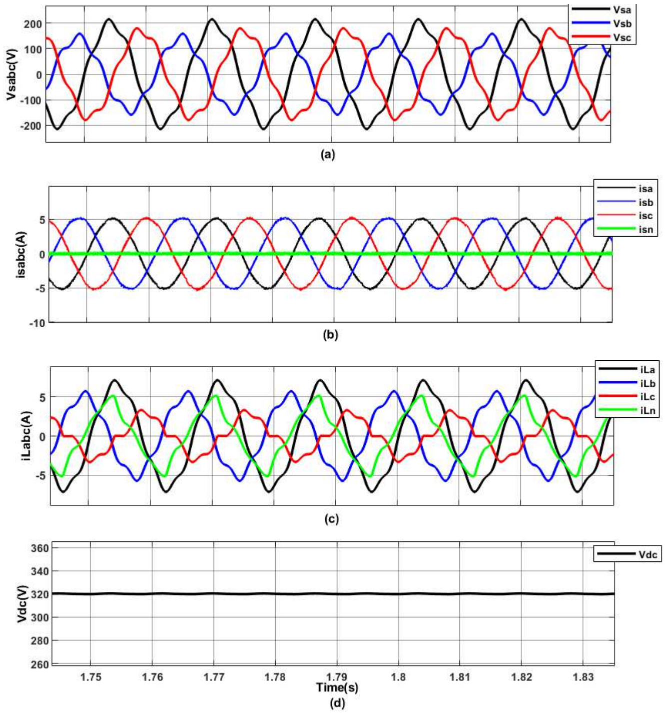
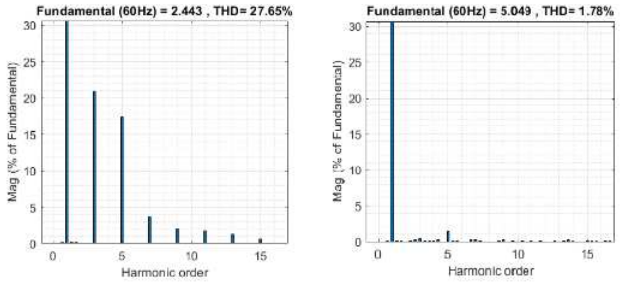


Fig. 7. (a):Three-phase unbalanced and distorted voltage (b): Grid current after compensation (c): Load current (d): dc-link voltage



(a) (b)

Fig. 8. (a): THD value of phase C current before compensation (b): THD value of phase C current after Compensation

IV. CONCLUSION

This paper presents a TCCF control strategy for a four-leg converter to compensate nonlinear and unbalanced load in the presence of a weak grid. In this approach, two CCF blocks are used to elicit the fundamental frequency positive sequence component of the load current and the converter and the required currents for compensation and rectification are regulated by the PR and P controller respectively. Moreover, another CCF block is used to extract fundamental frequency positive sequence component of the polluted source voltage to ensure good synchronization and estimated frequency from PLL. The four-leg converter under this strategy has a good performance in compensation and rectification mode. The TCCF approach is compared with the same case of TROGI and the simulation results show better performance of TCCF in improving grid power quality.

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