CONTROL OF A FOUR LEG INVERTER FOR UNBALANCED POWER NETWORKS

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***Abstract*—The operations of three-phase, four-leg inverter under unbalanced load conditions, have to be controlled. The inverter is proposed for hybrid power system applications, in order to provide simultaneous supply of three-phase and single-phase ac loads with balanced voltage and constant frequency. An outer voltage regulation loop is used to provide current reference to the inner current control loop to regulate the inverter current using PI regulators. A control strategy for the four-leg inverter based on the decomposition of the supply voltages and currents into instantaneous positive, negative and homo-polar sequence components using phasor representation is described, to ensure balanced voltage. The three sequences are controlled independently in their own reference frames as dc signals, so that the disturbance of the output voltage due to the load unbalances is eliminated. Aim is to develop a Psim model for the inverter control during unbalanced voltage conditions.**

Keywords— Four leg inverter; Hybrid power system; Current Control.

I. INTRODUCTION

In recent years there is growing interest in four leg converters for three-phase four-wire applications [1][2], such as controlled rectifiers, active power filters and many others applications that require neutral current control. One of the most promising applications of this topology is the Hybrid Power Systems (HPS). An HPS (Figure 1) can be generally defined as an electricity production and distribution system which consists of a combination of two or more types of electricity generating sources (e.g. wind turbine generators, solar photovoltaic panels, picohydro plant, diesel generators…). An HPS usually also includes an energy storage system. In such a system the different power generators interconnected with the AC load in an isolated grid can be subject of unbalanced voltages. Unbalanced utility grid voltages which is one of the most common utility voltage quality problem in this kind of system, may arise due to the simultaneous supply of three-phase and single-phase loads, a short-circuit or a starting up of a large induction machine. Such an unbalance in voltage at the point of common coupling can cause increased losses in motor loads and abnormal operation of sensitive electronic and electrical equipment. For low voltage distribution, when the HPS has a four wire configuration to supply both single-phase and three-phase loads, a 0-sequence current flows through the neutral conductor.

A major drawback in such HPS is voltage unbalance. Unbalanced loading conditions can occur in HPS for a variety of reasons. In general, small loads (relative to the power range of the system) are configured to draw power from only one phase. When several single-phase loads are placed on a distribution system, the fluctuating power required from each of these loads can cause unbalance in the power system. Even for dedicated three-phase motor drives, a significant (up to several percents) unbalance in the phase impedances can exist.

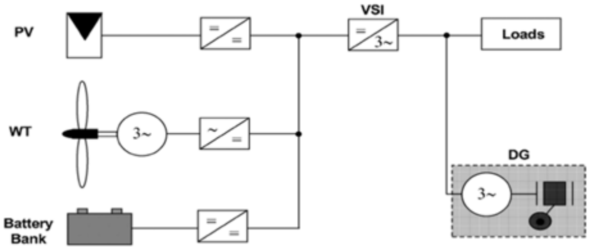


Fig. 1: HPS application with VSI

Today, most inverters are designed for balanced three-phase loads and consequently the associated control strategies are quite effective for three-phase, three-wire systems but are not able to manage loads that require a fourth (neutral) connection.

In three-phase applications with three-leg inverters, if the load requires a neutral point connection, a simple approach is to use two capacitors to split the dc link and tie the neutral point to the midpoint of the two capacitors. In this case, unbalanced loads will cause neutral currents that flow through the fourth wire between the load neutral point and the midpoint, distorting the symmetrical output voltage. Another drawback of this inverter topology is the need for excessively large dc-link capacitors [3].

Another possibility to provide a neutral connection for threephase,four-wire systems is to use a four-leg inverter. This topology involves an additional leg, expanding the control capabilities of the inverter using the same dc-link capacitor and voltage. The fourth leg provides a path for the neutral current when the load is unbalanced.

This paper proposes fully digital voltage and current controllers for a four-leg inverter allowing simultaneous balanced voltage supply of three-phase and single-phase ac loads in an HPS application. The controllers are implemented in two different reference frames rotating at fundamental frequency after the link.

Consequently, the line-to-neutral threephase output voltages Vaf , Vbf , and Vcf for the three-decomposition of the inverter ac voltage and current into positive, negative, and homopolar sequence components.

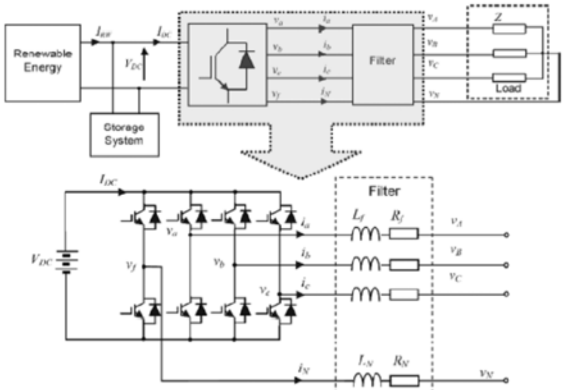


Fig. 2. Three-phase, four-leg inverter.

II. MODEL OF THE FOUR-LEG INVERTER UNDER UNBALANCED OPERATING CONDITIONS

The four-leg inverter in an HPS environment is described in Fig.2. As mentioned in Section I, its topology is characterized by the connection of the neutral point of the load to the midpoint of the fourth leg of the inverter. Due to load unbalances, an intruding current flows through the fourth wire between the load neutral point and the midpoint of the fourth leg of the inverter, and a voltage drop occurs, distorting the symmetrical output voltage. The three phases of the converter are independent of each other and the current flowing through each leg depends only on the position of the associated switches and its phase voltage.

Because studying the switches is not part of this study, the averaging technique [4] has been used to model the four-leg inverter. Assuming the switching frequency is much higher than the fundamental frequency of the ac signals, so that all voltage and current ripples due to the switches are negligible, the average inverter model can be obtained from the switching model. The dc-link voltage Vdc is kept at a constant value by controlling the energy flow from the storage system to the dc phase, four-leg inverter can be expressed as the product of the dc-link voltage and the duty ratios *daf , dbf* , and *dcf* .

The equations describing the behavior of the inverter voltages and currents under balanced and unbalanced conditions are expressed as follows:

$$\begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} = -V_{\mathrm{dc}} \begin{bmatrix} d_{af} \\ d_{bf} \\ d_{cf} \end{bmatrix} + R_f \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$- R_N \begin{bmatrix} i_N \\ i_N \\ i_N \end{bmatrix} - L_N \frac{d}{dt} \begin{bmatrix} i_N \\ i_N \\ i_N \end{bmatrix}$$

$$i_a + i_b + i_c + i_N = 0$$

where R_f and R_N , and *Lf* and L_N are the resistances and the inductances of the inverter filter, V_{AN} , V_{BN} , and V_{CN} are the line-to-neutral filter output voltages, *ia, ib* , and *ic* are the threephase inverter output currents, and i_N is the neutral current.

III. DECOMPOSITION INTO SYMMETRICAL COMPONENTS

In terms of control loop design, the conventional control strategy of the four-leg inverter uses voltage and current dq0-components. If the load is balanced, the d- and qcomponents are DC quantities and the 0-component is zero. If the load is unbalanced both d- and q-components contain an additional AC quantity, which oscillates with the double frequency of the output voltage. The 0-component is not zero and oscillates with the same frequency as the output voltage. To solve this problem the proposed control strategy uses the symmetrical components of the output voltage and current decomposed into dq DC quantities. According to the Fortescue theorem, three-phase variables can be symmetrically decomposed into positive, negative and homopolar sequence components. Therefore, the inverter output voltages can be expressed as:

$$\begin{bmatrix} \bar{v}_{AN} \\ \bar{v}_{BN} \\ \bar{v}_{CN} \end{bmatrix} = \begin{bmatrix} \bar{v}_{AN,p} + \bar{v}_{AN,n} + \bar{v}_{AN,h} \\ \bar{v}_{BN,p} + \bar{v}_{BN,n} + \bar{v}_{BN,h} \\ \bar{v}_{CN,p} + \bar{v}_{CN,n} + \bar{v}_{CN,h} \end{bmatrix}.$$

where (V_{AN} p , v_{BN} p , V_{CN} p ,) is the positive-sequence voltage, (V_{AN} n , v_{BN} n , V_{CN} n) is the negativesequence voltage and (V_{AN} h , v_{BN} h , V_{CN} h) is the homopolar sequence voltage.

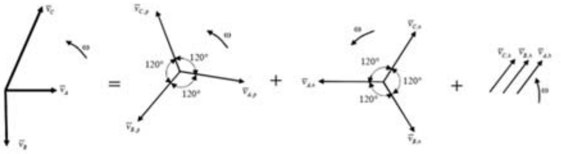


Fig. 3: Decomposition of a three-phase unbalanced system in three balanced systems

The transformation of the *ABC* signals into symmetrical components can be expressed by the following compact form:

$$[\bar{x}_{i,p}] = [F_p] \cdot [\bar{x}_i]$$

$$[\bar{x}_{i,n}] = [F_n] \cdot [\bar{x}_i]$$

$$[\bar{x}_{i,h}] = [F_h] \cdot [\bar{x}_i]$$

where *x* can be voltage or current, ¯*x* denotes the phasor of *x*, and *i* = *A*, *B*, *C.* The transformation matrices *Fp, Fn* , and *Fh* have the following expressions:

$$[F_p] = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix}$$

$$[F_n] = \frac{1}{3} \begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix}$$

$$[F_h] = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

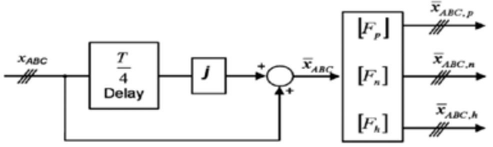
where $a = ej2\pi/3$.

Let us consider X_{ABC} the three-phase (balanced or unbalanced) sensed voltage or current in the output filter of the investigated four-leg inverter.

The mathematical expression of this signal is:

$$x_{ABC} = x_{ABC\,\max} \cos\left(\omega t + \varphi_{ABC}\right)$$

For the proposed control strategy, a simple way to obtain the symmetrical components of the supply voltage and current is presented in Fig. 5.



This method implies delaying the measured voltage and current X_{ABC} by one-fourth of the period at the fundamental frequency (T = 1/f, f = 50 Hz). The addition of the measured voltage and the same signal delayed by onefourth of the period and multiplied by the complex operator j ($j = \sqrt{-1}$) gives the phasor representation $\overline{X}_{ABC}$. Using this representation and the transformation matrix (Fp, Fn , and Fh), the positive, negative, and homopolar sequences components are obtained. Fig. 6 shows the real part of the three-phase system (X_{ABC}) decomposition into symmetrical components and the effect of the delay when applying the method proposed earlier. Until 0.04 s, the three-phase system is balanced and becomes unbalanced after this moment. For the inverse transformation, it is sufficient to add phase-byphase the real part of the positive, the negative, and the homopolar sequences in order to regain the original sensed signal.

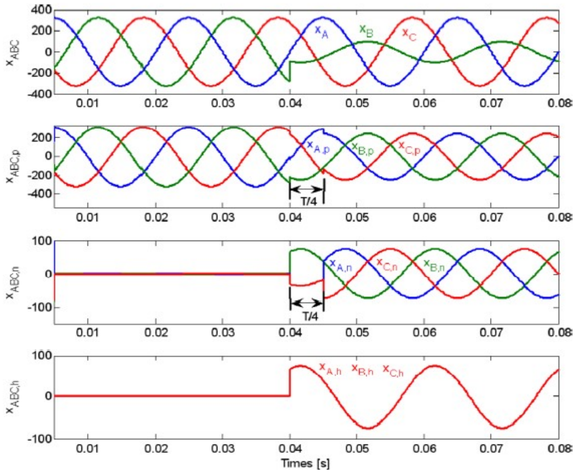


Fig. 4. Three-phase system decomposition into symmetrical components.

From Fig. 4, the following conclusions can be drawn.

1) Starting with three real variables, X_A, X_B , and X_c , after transformation, we obtain three new sets of three real variables: X_{ABC},p, X_{ABC},n, and X_{ABC},h (positive, negative, and homopolar sequence components).

2) The three sequence components are completely independent of each other, from the amplitude point of view.
3) The three sequence components turn at the same speed and in the same direction. Only the negative system has reversed phase sequence.

4) The negative and the homopolar sequences appear only when the original three-phase system is unbalanced.

5) The homopolar sequence components are superposed.

Because the symmetrical components are always balanced, the voltage and current regulation is performed in a dq syn- chronous reference frame rotating at the fundamental frequency.

Thus, using a positive reference frame, which rotates counterclockwise, the positive sequence *dq* voltages and currents appear as dc signals. In contrast, the dc quantities of the negative sequence *dq* voltages and currents are obtained using a negative reference frame, which rotates clockwise. The homopolar sequence voltage or current appears as a disturbance in the *0*-variable at the fundamental angular frequency ω in any rotating system reference frame (positive or negative), while *d* and *q* components are inexistent. Thus, it is not possible to rotate the *0*-variable voltage in order to transform it into a dc signal and to facilitate its regulation. As shown in Fig. 4, the vectors of the homopolar sequence system are in phase and equal in amplitude. They are also independent, from the point of view of the amplitude, with regard to the positive- and negative-sequence systems. Thus, it is possible to apply a spatial rotation of 120° and 240° to the homopolar phasors *B* and *C* and the transformation matrix F_h becomes

$$[F_h^*] = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ a & a & a \\ a^2 & a^2 & a^2 \end{bmatrix}.$$

The obtained three-phase balanced voltage system is transformed in dc *dq* signals using the rotating negative reference frame. Once transformed in dc signals, the homopolar sequence can be easily regulated by PI controllers. This technique, which allows obtaining dc signals, and thus, a good regulation of the homopolar sequence voltage and current, is possible because the applied transformations do not affect the amplitude of the processed signals. The complete transformation of the measured signals (voltage and currents). As it can be seen, only the real part of the phasor representation is used to obtain dc signals.

IV.VOLTAGE AND CURRENT REGULATION

The voltage and current signals obtained after decomposition into symmetrical components are regulated using an inner current loop controller and an outer voltage loop controller. Both loops are disposed in three-channel arrangement (Figure 5). The first channel allows controlling the positive sequence of the current and voltage, the second is for the negative sequence and the third is for the homopolar sequence.

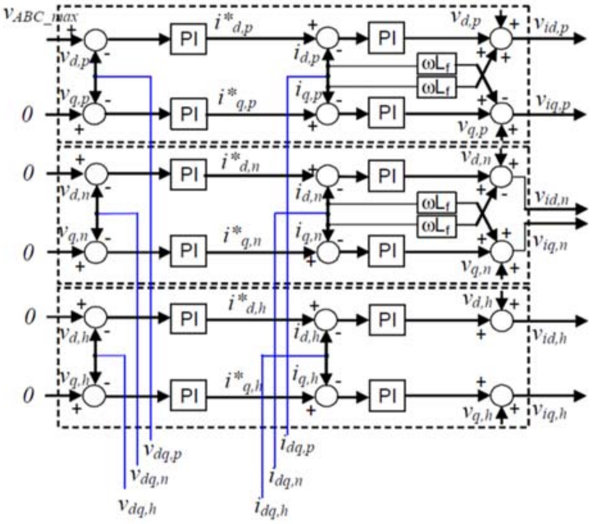


Fig. 5: Voltage and current regulation loops

In the inner current loop, the positive-sequence current (id,p, iq,p, in the first channel of the control structure presented in Fig. 8) is regulated in the positive reference frame. The terms ωLfiq,p, -ωLfid,p are inserted to decouple dq axes dynamics. The negative-sequence current (id,n, iq,n) in the second channel of the control structure is controlled in the negative rotating reference frame. The homopolarsequence current (id,h, iq,h) in the third channel of the control structure is controlled in the negative rotating reference frame. The outer voltage loops give the reference currents {i* d,p, i* q,p, i* d,n, i* q,n, i* d,h, i* q,h} in order to keep the measured voltages at constant values. The positive-sequence voltage vd,p is compared with the desired output voltage amplitude and the error is processed in a PI controller. All the remaining sequence voltages are kept at zero value using the same procedure. These voltage set-points correspond to a balanced three-phase AC voltage. The control signals to be applied to the inverter are obtained using the inverse Park and

Clarke transformations with the addition of the symmetrical components. The addition is carried out phase by phase, using only one phase from the homopolar sequence

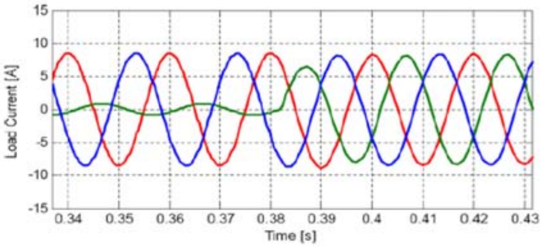


Fig. 6. Simulation result of the load current.

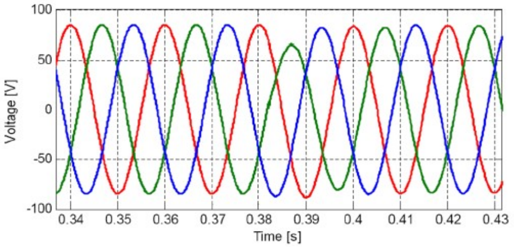


Fig. 7. Simulation result of the load voltage

V. OUTLOOK AND CONCLUSIONS

The issues in the modeling and control of four leg inverter were investigated. The ability of a four leg inverter in dealing with unbalanced and non-linear loads was presented. It was established that in order to deal with unbalanced load, the loop gain must have sufficient gain at 2w where w is the fundamental output frequency.

Operation of a four-leg inverter under unbalanced load conditions for HPS applications has been investigated. The four-leg inverter is controlled using an innovative control strategy based on the decomposition of the supply three-phase voltage and current into instantaneous positive, negative, and homopolar sequence components using phasor representation. The proposed control strategy has the ability to decompose into dq dc quantities not only the positive and negative current and voltage sequences, but also the homopolar sequence. Consequently, regulation has been easily done with classical PI controllers.

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