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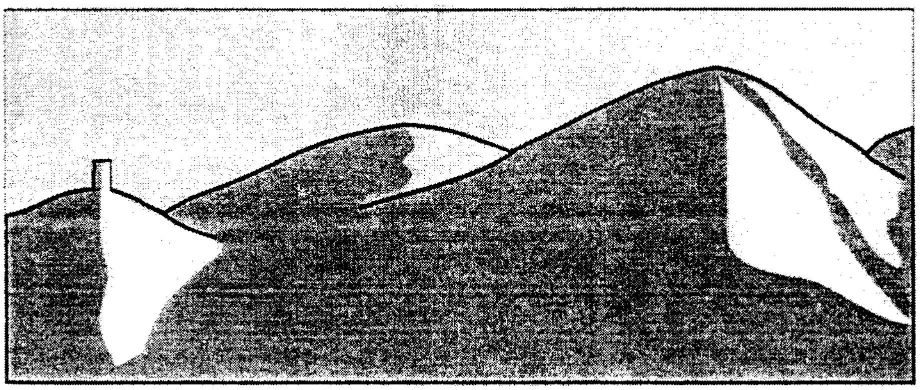

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SPACE VECTOR APPLICATIONS IN POWER SYSTEMS

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Abstract – In this paper, the spatial vector transformation, as used in machine vector control, is applied to the power system analysis. The proposed methodology is applied to power electronics converters, transformers and transmission lines, as well as to power sources and loads with different connections (delta-wye). This method can be applied to steady state, transient, unbalanced sources and harmonic analysis. Models obtained using this method are as simple as the per phase schematic approach. The instantaneous active and reactive power concepts can be expanded and generalized, and new power system control strategies can be developed when power electronics converters are used. Steady state, transient behavior, and harmonic analysis examples and applications using spatial vector theory are presented to illustrate the methodology performance and its advantages. An extension of this method can be applied in faulted systems (unbalanced) using instantaneous symmetric components in polyphase balanced circuits.

I. INTRODUCTION

Power systems have been analyzed using matrix transformations for several decades (Clark, Karrembaüer, Fortescue, etc.) [1,2,3]. The modal representation method uncouples symmetric power systems equations. This technique has been widely used to model electric systems in steady state, balanced and unbalanced operation, as well as during transient, dynamic or harmonic analysis. Nevertheless, achieving the modal uncoupling of the system equations can be a very hard work in complex polyphase networks. To avoid this problem some works have been presented dealing with the development of power system analysis techniques in non-transformed coordinates [4].

During the last decade, the control of induction machines using space vectors and oriented field transformations has been thoroughly developed [4,5]. Spatial vector transformations are derived from Symmetric components transformations [6], giving a simple and concise representation, since the zero sequence model is not needed when neutral wire is not connected and the negative sequence model is a conjugate complex representation of the positive spatial vector scheme. One advantage of the spatial vector transformation is the reduction from six real machine equations (three for stator and three for rotor) to a pair of complex equations (one for stator and other for rotor). The other advantage is the representation of three time varying quantities with one spatial-time complex variable.

The symmetric components transformation uncouples symmetric and cyclic polyphase systems. Symmetric systems such as transmission lines, transformers and loads can be uncoupled by any Kerrembaüer transformation, but the main advantage with the symmetric components transformation is the uncoupling of cyclic systems as induction motors and round rotor synchronous machines. Salient pole synchronous machines, unbalanced loads, long non-transposed lines, and non symmetric faults can not be uncoupled by any generic transformation. Park's transformation or any other rotational transformation can be used to simplify the synchronous machine model, but in these models the transformed coordinates systems (dq) are straight coupled. Since the spatial vector transformation is directly derived from symmetrical components, it can also be applied to uncouple the power system equations on balanced systems.

A new rectifier control technique has been developed to reduce harmonic distortion, improve the power factor and increase the power quality [7,8]. This spatial vector control is based on active rectification using IGBTs or GTOs power switches. The spatial vector control is simpler than the other control techniques, and the analysis of the AC/DC converter can also be improved. Interconnection between power system and rectifiers can be modeled using the spatial vector transformation. For this purpose, power system representation using spatial vectors is a very useful approach.

In this paper, a brief section introducing the main spatial vector definitions is included. Spatial vector transformation using a pseudo-hermitic definition is employed and a very useful conservative transformation is achieved. Instantaneous active and reactive power definitions are extensively used. A physical interpretation of the instantaneous active and reactive power is obtained using the Pointing's vector concept. Transmission line, transformer, load and machine models are developed using the spatial vector definition. Steady state, transient analysis, and harmonic load flow are shown as examples to prove the advantages of the spatial vectors in power system analysis including electric machines and power electronic converters.

II. DEFINITIONS

Traditionally the power systems have been analyzed using symmetrical components or any other Karrembaüer transformation [1,2,3]. These polyphase transformations uncouple symmetric and cyclic systems. In balanced power systems or in systems without a neutral wire return, the holonomic or zero sequence component is zero. Positive or negative sequences have a similar behavior, especially in symmetric polyphase systems. During the last decade the use of spatial vector transformations have been widely applied to the dynamic control of the electrical machine [4,5]. This methodology simplifies the machine model and introduces a more compressive and simple variable set. The spatial vector transformation can be defined as:

$$\mathbf{x} \equiv \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & e^{j\frac{2\pi}{3}} & e^{j\frac{4\pi}{3}} \end{bmatrix} \cdot \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} = \\ = x_\alpha(t) + j\,x_\beta(t) = x(t)e^{j\xi(t)} \tag{1}$$

The coefficient $\sqrt{2/3}$ is a hermitic factor needed to conserve power between coordinates systems. Factor $1/\sqrt{3}$ is obtained from the hermitic symmetrical components transformation [5], and $\sqrt{2}$ is necessary to reproduce the same instantaneous active power between the original coordinates and the spatial vector frame in a balanced system. Figure 1 shows a spatial vector interpretation of the vector transform 1.

Since the instantaneous spatial power must remain in agreement with the conventional complex power definitions used in the balanced steady state, it is necessary to express it as:

$$\vec{s}(t) \equiv \vec{v}(t) \cdot \vec{i}^{\,*}(t) = p(t) + j\,q(t) \tag{2}$$

Where $\vec{v}(t)$ and $\vec{i}^{\,*}(t)$ are the spatial vectors defined as:

$$\vec{v}(t) \equiv \sqrt{2/3}\left[1, e^{j2\pi/3}, e^{j4\pi/3}\right] \cdot [v_a(t), v_b(t), v_c(t)]', \tag{3}$$

$$\vec{i}^{\,*}(t) \equiv \sqrt{2/3}\left[1, e^{j4\pi/3}, e^{j2\pi/3}\right] \cdot [i_a(t), i_b(t), i_c(t)]'. \tag{4}$$

Using spatial vector definitions 3 and 4, and separating the real and imaginary elements of the resultant expression, the instantaneous real, reactive and apparent powers are:

$$\vec{s}(t) = p(t) + j\,q(t) = [v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c] + \\ j\frac{\sqrt{3}}{3}[i_a \cdot v_{bc} + i_b \cdot v_{ca} + i_c \cdot v_{ab}]. \tag{5}$$

The definitions given in 5 are valid under any condition, that is, either using three or four wires, in transient or steady state, in balanced or unbalanced condition, or considering sinusoidal or non-sinusoidal waveforms. The real part in Eq. 5 is equal to the classical instantaneous power definition, but the imaginary part is not so well known, and disagrees in some special cases with the vector definition. In a balanced, steady state and sinusoidal three-phase system, the instantaneous active and reactive power are time invariant, because the spatial voltage vector 3 and the spatial current vector 4 have constant amplitude, and their relative phases are also constant. In this condition, the classical and the vector definitions agree, but in presence of non-sinusoidal waves, or in an unbalanced system, the classical and vector power definitions have some important differences.

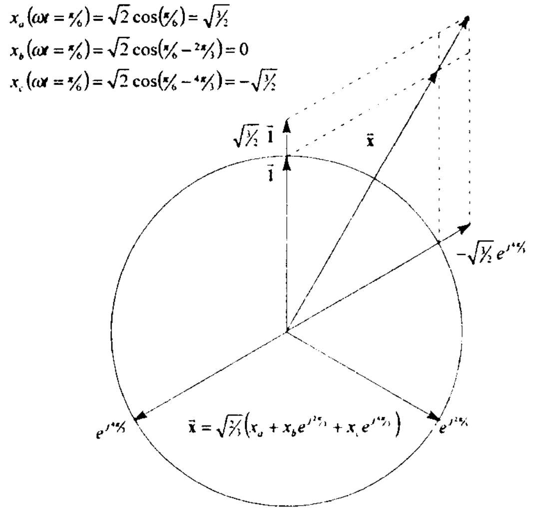

Fig. 1 Graphic interpretation of the spatial vectors transformation

To give a physical interpretation of the definition 2, it is necessary to remember the relationship existing between the electromotive force e, and the electrical field intensity $\vec{\mathbf{E}}$ and also the one between the magnetic field intensity $\vec{\mathbf{H}}$ and the current i. The vector multiplication of the electrical field intensity $\vec{\mathbf{E}}$ and the magnetic field intensity $\vec{\mathbf{H}}$ is defined as the Pointing's vector $\vec{\mathbf{S}} = \vec{\mathbf{E}} \times \vec{\mathbf{H}}$ [5]. This spatial-temporal vector represents the power flow by unit area of the electromagnetic field. For example, in a given point of the air-gap on the rotating electric machine, the Pointing's Vector $\vec{\mathbf{S}}$ has two components, one in the radial direction that determines the active power flow, and the other in the tangential component that maintains the rotating electromagnetic field required during the operation. In a three phase transmission line the phenomena is similar, but the instantaneous active power $p(t)$ corresponds to the longitudinal component of the Pointing's Vector and the reactive power $q(t)$ is related to the tangential or rotational component of this vector. As the current i and the magnetic field intensity $\vec{\mathbf{H}}$ are related through the Ampère's Law, and the electromotive force e is obtained by the integration of the electric field intensity $\vec{\mathbf{E}}$, it is reasonable to think that the instantaneous active power $p(t)$ is narrowly related to the radial component of the Pointing's Vector $\vec{\mathbf{S}}$, and the instantaneous reactive power $q(t)$ depends on the imaginary part of this vector.

III. POWER SYSTEM MODELS

3.1 Delta-Wye Loads and Simple Sources

Figure 2 shows a load or simple source in delta or wye connection. In a balanced system the neutral current is zero and is not necessary to consider it. Passive loads are modeled assuming zero voltage in the power source. Active loads and simple generators can be modeled using balanced voltages in the polyphase source.

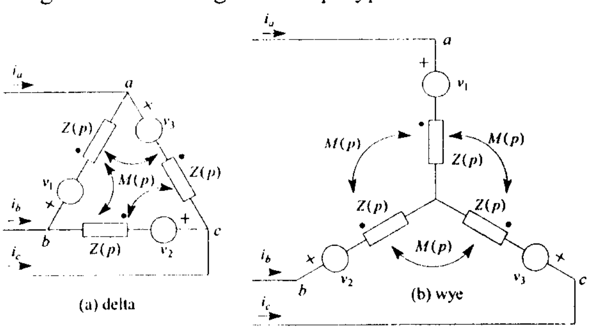

Fig. 2 Operational loads and simple sources connected in (a) Delta; (b) Wye

Delta connection (a) can be modeled using the following approach:

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} + \begin{bmatrix} Z(p) & M(p) & M(p) \\ M(p) & Z(p) & M(p) \\ M(p) & M(p) & Z(p) \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \quad (7)$$

Applying spatial vector transformation 1 to Eq. 6 and Eq. 7:

$$\vec{i}_s = \sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \Rightarrow$$
$$\sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{e^{j\pi/6}}{\sqrt{3}} \vec{i}_s \quad (8)$$

$$\sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \left\{ \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} v_b \\ v_c \\ v_a \end{bmatrix} \right\} = \sqrt{3}\, e^{j\pi/6}\, \vec{v}_s \quad (9)$$

$$\sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \cdot \begin{bmatrix} Z(p) & M(p) & M(p) \\ M(p) & Z(p) & M(p) \\ M(p) & M(p) & Z(p) \end{bmatrix} =$$
$$\sqrt{\tfrac{2}{3}} \left(Z(p) - M(p)\right) \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \quad (10)$$

$$\sqrt{3}\, e^{j\pi/6}\, \vec{v}_s = \vec{e} + \frac{e^{j\pi/6}}{\sqrt{3}} \left(Z(p) - M(p)\right) \vec{i}_s$$
$$\Rightarrow \quad (11)$$
$$\vec{v}_s = \frac{e^{-j\pi/6}}{\sqrt{3}} \vec{e}_s + \frac{Z(p) - M(p)}{3} \vec{i}_s$$

Where:

$$\vec{e}_s \equiv \sqrt{\tfrac{2}{3}} \begin{bmatrix} 1 & e^{j2\pi/3} & e^{j4\pi/3} \end{bmatrix} \cdot \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T$$

Equation 11 shows the spatial model for delta connection. The spatial electromotive force is a line to neutral voltage with a 30° lag. Z(p) impedance is divided by 3 in the spatial model. The same results can be obtained when a delta-wye transformation is performed.

Wye connection (b) can be modeled using the following approach:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} + \begin{bmatrix} Z(p) & M(p) & M(p) \\ M(p) & Z(p) & M(p) \\ M(p) & M(p) & Z(p) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (12)$$

Applying spatial vector transformation 1 to Eq. 12:

$$\vec{v}_s = \vec{e}_s + \left(Z(p) - M(p)\right) \vec{i}_s \quad (13)$$

Equation 13 shows the spatial model for wye connection.

3.2. Transmission Line Model

Figure 3 shows a three-phase transmission line model, including line-line and line-ground capacitance, self and mutual inductance and resistance. Using Eq. 11 and 13, the transmission line model in spatial vector coordinates can be obtained as:

$$\begin{bmatrix} \vec{v}_{in} \\ \vec{i}_{in} \end{bmatrix} = \begin{bmatrix} A(p) & B(p) \\ C(p) & D(p) \end{bmatrix} \begin{bmatrix} \vec{v}_{out} \\ \vec{i}_{out} \end{bmatrix} \quad (14)$$

Where:

$$A(p) = 1 + R_L(C_M + 3C_G)p + (L_L - M_L)(C_M + 3C_G)p^2$$

the spatial vector of the ac current $\vec{i}_{rec}$ can be obtained from:

$$\vec{v}_{sys} = \vec{v}_{rec} + L_{rec} p \vec{i}_{rec} \qquad (19)$$

Where:

$$\vec{v}_{rec} = \sqrt{2/3}\begin{bmatrix}1 & e^{j2\pi/3} & e^{j4\pi/3}\end{bmatrix}\cdot\begin{bmatrix}v_A \\ v_B \\ v_C\end{bmatrix} =$$

$$= \sqrt{2/3}\begin{bmatrix}1 & e^{j2\pi/3} & e^{j4\pi/3}\end{bmatrix}\cdot \mathbf{Sw}\cdot V_{dc}$$

and **Sw** is the connectivity vector, whose elements are 1 if the upper switch is on and zero if the lower is on for each bridge branch. The rectifier spatial vector $\vec{v}_{rec}$ has only seven possible states, shown in figure 6.

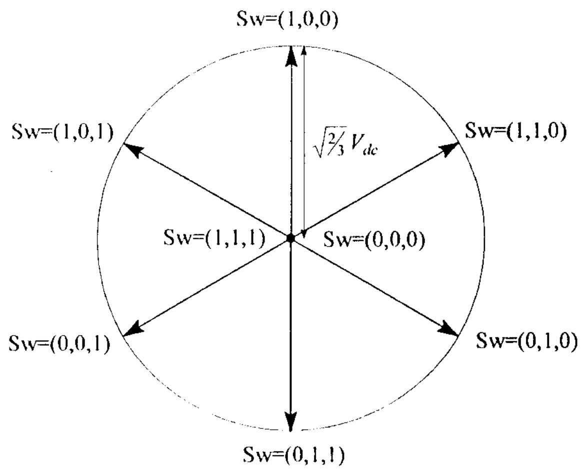

Fig. 6 Voltage spatial vector $\vec{v}_{rec}$ as function of the switching vector **Sw** for the voltage source rectifier bridge.

In rectifiers feeding a constant current source, the rectifier current spatial vector $\vec{i}_{rec}$ behaves as the voltage spatial vector in a rectifier feeding a constant voltage source (figure 6). Nevertheless, during the commutation intervals the current spatial vector can not change instantaneously between two positions. Hence, there is a smoother variation along the spatial circle path due to the inductance L_{rec}. During commutations, the line current changes continuously, dropping in one phase and increasing in the other. In these conditions, the magnitude of the current spatial vector $|\vec{i}_{rec}|$ is dependent on the switching strategy. For example, in a current delta controlled bridge, the current spatial vector draws a circle at constant angular speed. In any other case, a more detailed circuit analysis of the commutation process must be performed in order to evaluate the current spatial vector trajectory. Analysis of power system including rectifier bridges needs accurate bridge control system modeling.

IV. SIMULATION

Figure 7 shows a simple power system including a delta connected source, a medium length line transmission, a Dy_{11} power transformer and an active rectifier bridge working as a voltage source, whose instantaneous active and reactive power is controlled using current delta modulation. Model parameters used in this example are listed in Table I. The active power reference is 0.08 and the reactive reference is 0.06 lagging. All values are expressed in the per unit system.

Figure 8 shows the current space vector in the transformer output. The hexagonal space wave is generated by the six bridge connection possibilities. The voltage wave is also affected by the same operating factors, but the network response produces lower wave distortions. The instantaneous active and reactive power functions have a medium value near its respective reference, with oscillations due to harmonic currents and voltages.

L_g	R_L	$L_L - M_L$	$C_M + 3C_G$	L_e
0.03	0.005	0.05	0.1	0.2
R_{T_1}	R_{T_2}	L_{T_1}	L_{T_2}	M_T
0.005	0.005	100.05	100.05	100.00

Table I: Network Example Parameters

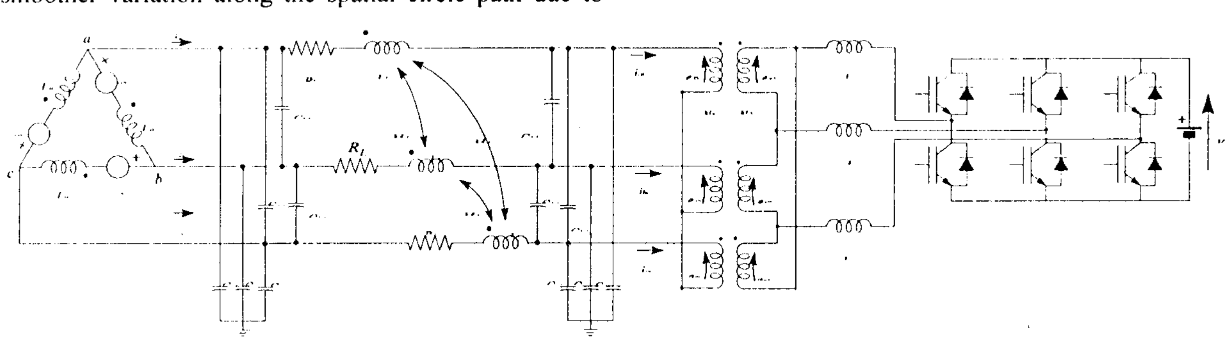

Figure 7. Power system example

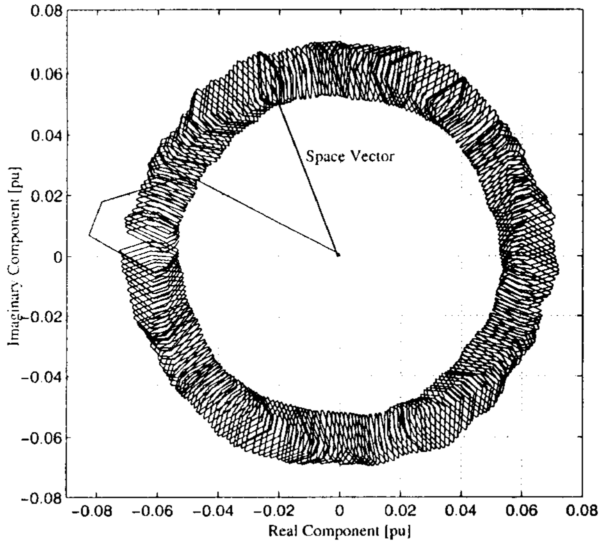

Fig. 8, Current space vector in the power transformer output

CONCLUSIONS

In this paper the space vector transformation applied to power system analysis has been presented. Space models are very simple and give a better interpretation of the polyphase circuit analysis, including coupled circuits. Space vector transformation is a useful method to combine power electronic control and power system analysis. This technique can be applied in both steady and transient state, and when harmonic flow is present. A very simple example has been developed to illustrate the visualization advantage of the proposed method.

The main limitation presented by this method is the symmetric restriction forced by the space vector transformation, that can only be applied to symmetric or cycle matrix representation. The integration between machine controllers and power system analysis is achieved, also a better knowledge of the interrelation between these methodologies can be obtained using space vector transformation in the pseudo-hermitic formulation.

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$$A(p) = 1 + R_L(C_M + 3C_G)p + (L_L - M_L)(C_M + 3C_G)p^2$$

$$B(p) = R_L + (L_L - M_L)p$$

$$C(p) = (C_M + 3C_G + R_L(C_M + 3C_G)^2 p + +(L_L - M_L)(C_M + 3C_G)^2 p^2)p$$

$$D(p) = A(p)$$

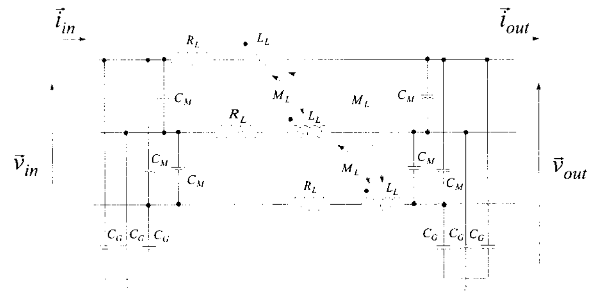

Fig.3 Transmission Line Model

Equation 14 represents the spatial vector model of the transmission line. The same procedure can be applied to long transmission lines introducing the spatial vector definition into differential equations that model the multi-port system. The model obtained using symmetrical components is equal to the model developed using spatial vector theory.

3.3 Transformer Model

Figure 4 shows a three-phase Yd11 ideal transformer. Delta-wye connections can be analyzed using spatial vectors as follows:

$$e_{x_1} = a \cdot e_{x_2} \qquad e_{y_1} = a \cdot e_{y_2} \qquad e_{z_1} = a \cdot e_{z_2} \tag{15}$$

Where:

$$a = N_1 / N_2$$

$$\begin{bmatrix} v_{ab_1} \\ v_{bc_1} \\ v_{ca_1} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_{x_1} \\ e_{y_1} \\ e_{z_1} \end{bmatrix} = \begin{bmatrix} a & -a & 0 \\ 0 & a & -a \\ -a & 0 & a \end{bmatrix} \begin{bmatrix} e_{x_2} \\ e_{y_2} \\ e_{z_2} \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} v_{ab_2} \\ v_{bc_2} \\ v_{ca_2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_{x_2} \\ e_{y_2} \\ e_{z_2} \end{bmatrix} \tag{17}$$

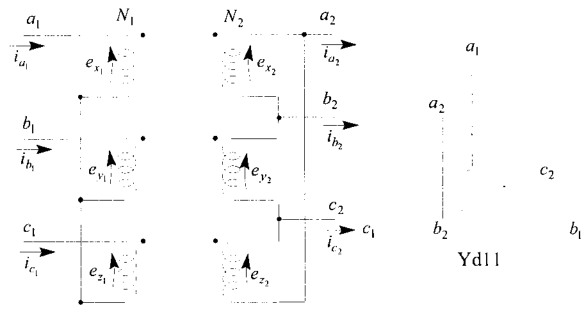

Fig.4 Ideal Three Phase Transformer

Applying the spatial vector transformation 1 to Eq. 16 and 17, the following result can be easily obtained:

$$\vec{v}_1 = \sqrt{3}\, a\, e^{j\pi/6} \cdot \vec{v}_2 \tag{18}$$

Non ideal transformers can be modeled using the coupling circuit theory applied in the load and source model developed in Eq. 6 to 13. Other power transformers such as Zig-Zag, auto-transformers, phase shifting or multiwinding transformers can be easily analyzed using the spatial vector transformation. Equation 18 shows the model simplicity, in harmonic or transient analysis. In steady state analysis the results agree with the classic transformer considerations.

3.4. Rectifier Bridge Model

The spatial vector model of the rectifier bridge is very simple when three switches are simultaneously on. In this case the rectifier will be modeled for two cases: Feeding a constant voltage source or a constant current source, as shown in figure 5.

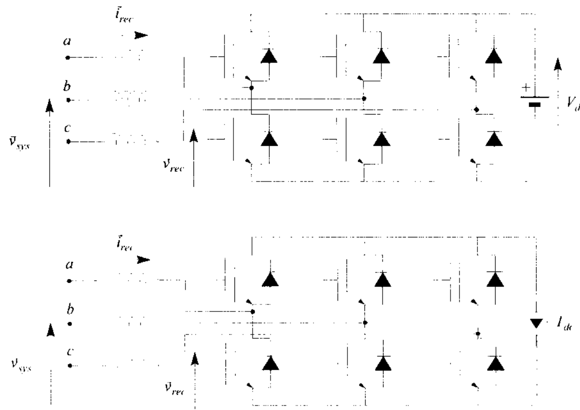

Fig. 5 Active rectifier with voltage or current sources in the DC side

When the rectifier feeds a constant voltage source, the bridge connectivity defines directly the spatial vector $\vec{v}_{rec}$. Knowing $\vec{v}_{rec}$, $\vec{v}_{sys}$ and the inductance L_{rec} between the power system and the rectifier bridge, the spatial vector of the ac current $\vec{i}_{rec}$ can be obtained from: