A Laplace-Clarke Distributed HF Model of Asynchronous Machines

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Abstract: - An innovative three-phase distributed model is presented for asynchronous machines operating at high-frequency. The model is useful to study the propagation of surge along the stator windings of the machines that is excited by PWM-inverter source or fault waves that occur in the connected line.
The new model is derived from single-phase models traditionally considered in literature. The use of time-space Clarke vectors allow the introduction of mutual coupling between phase winding and the integration of the model extending the methods that had been developed for the single-phase case by substituting real time-space variables with complex functions.
A numerical method useful to simulate the distributed model is presented too. This is based on Laplace transformation of the Clarke waves.
Finally, the first numerical results, carried out by applying a unitary steep-surge and a standard IEEE wave for insulation test to the obtained equivalent distributed networks, confirm the model validity and permit to underline the required low computational cost of the approach.

Key-Words: - Machines surge, Clarke transformation, High frequency model, Three-phase distributed model

1 Introduction

The classic dynamical theory of asynchronous machines is based on the systematic use of space-vectors. According with Clarke approach, the electric-magnetic-mechanical system is described, in quasi-steady conditions, by ordinary differential equations. In this way, the machine is regarded as an equivalent lumped-constants circuit on the $\{\alpha,\beta\}$ axis and the propagation phenomena are absent.
When the frequency of the voltage arises, the geometric dimensions of the stator windings become comparable with the wavelength of the electromagnetic field involved and the ordinary model lost its validity. With the hypothesis that the field structure is Transverse ElectroMagnetic (TEM) or *quasi*-TEM, the windings have to be considered as distributed network of inductances and capacitances mutually coupled and series resistances. In this way, propagation phenomena appear and the describing differential equations become of partial type. The integration of these hyperbolic equations is very difficult; this is due not only to the mathematic aspects involved but also to the difficult of measured or calculated the distributed parameters.
In the present work an innovative approach based on Clarke vectors in high frequency is proposed for a distributed constants model, in which the presence of capacitive and inductive parameters permits to consider the propagation of steep-fronted surges, i.e. due to PWM-inverter source or to faults that occurring in the connected line. Because the related voltage waves are revisited as time-dependent space-vectors, it is possible to extend the resolution techniques just adopted for one-phase winding to the analyzed three-phase case.
A simulation method based on Laplace Transform of the obtained Clarke model is also presented. The first numerical results, carried out by applying a unitary steep-surge and standard IEEE wave for insulation test to the obtained equivalent distributed networks, confirm the model validity and permit to underline the required low computational cost of the approach [5].
The following points are covered in the next sections. In Section 2 classical single-phase models of the winding present in literature are rewieved and a new distributed three-phase model is proposed. Section 3 derives, by using the time-space instantaneous symmetric components, the HF Clarke model of the machine. Section 4 proposes a numerical method of simulation. Finally, Section 5 presents two practical cases which results are compared with those that are present in literature.

2 The three−phase model

The problem of wave propagation in the windings of A.C. electrical machines has received much attention in recent years. Recent trends in power systems have imposed that steep-fronted switching surges are often encountered in many industrial applications that require the use of PWM Voltage Source Inverter (PWM-VSI).
In particular, PWM-VSIs operate nowadays with Insulated Gate Bipolar Transistors able to generate steep fronted pulses at high switching frequencies, close to 20 KHz [1].

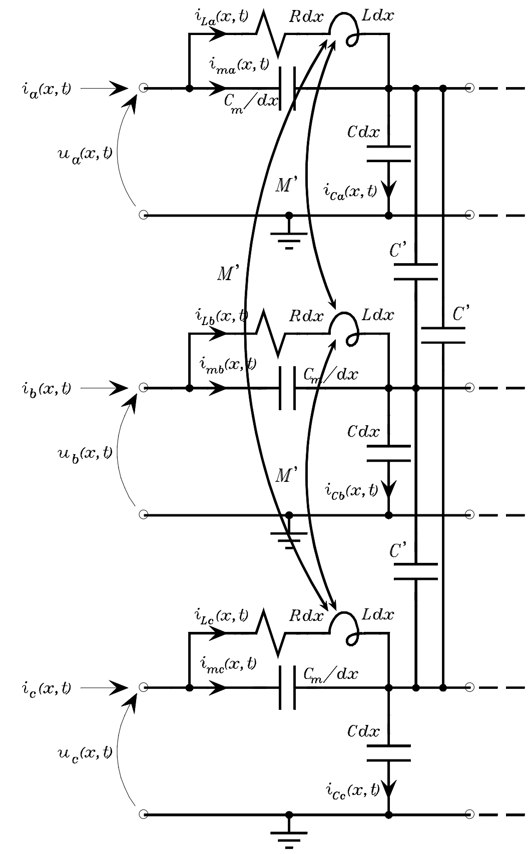

Fig.1. The proposed three-phase model.

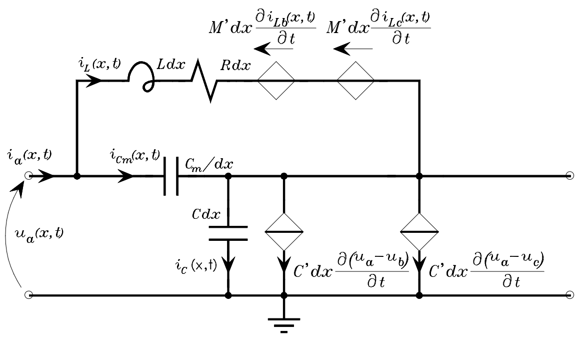

Fig. 2. Representation of elementary coupling between phases.

Another cause of steep-fronted surges is due to overvoltages caused by faults near the machine. Voltage and current waves are present in this case also. They can cause problems to the windings' insulation.

Apart from the techniques used for the parameters calculation, we propose a new three-phase model, useful for studying the time-space dynamic of machine windings.

The Clarke transformation leads the three-phase model to an equivalent complex one. In this way it is possible taking into account a lot of circuital parameters as regards the available models.

The proposed model is represented in Fig. 1; the following circuital parameters are present:

- a self-inductance L, concerning every coil;
- a capacitance C_m between coil and coil;
- equivalent resistance R, representing conductive and skin-effect losses;
- stray capacitance respect to the ground (neglecting the flux penetration in the iron core [2]).

According to the literature [2], mutual capacitances between non-adjacent coils are neglected. It's fundamental to remember that results $C_m << C$; so many authors neglect the C_m term.

Between the coils of the same winding mutual inductances are present. In further studies we will consider them. In case of form wound windings mutual inductances, taking into account the shielding effect in the iron core due to high frequencies [4], are negligible. On the contrary, in random wound windings, mutual inductances, observing that coils are very close, must be taken into account.

As it is shown in Fig. 1, some mutual parameters are present between phase windings (M', C'). They usually are not taken into account. An exception is represented by approximated lumped constants models present in literature. We assume that this parameters are present only at the same abscissa x.

Taking into account this coupling, it is useful to consider the representation by voltage and current impressed generators (see Fig. 2).

Expressed the model in phase-domain, by using Clarke transformation, we obtain the following equations:

$$\begin{aligned}&\frac{\partial^2 \overline{u}_{\alpha\beta}(x,t)}{\partial x^2} - (L-M')(C+3C')\frac{\partial^2 \overline{u}_{\alpha\beta}(x,t)}{\partial t^2} \\ &+ (L-M')C_m\frac{\partial^4 \overline{u}_{\alpha\beta}(x,t)}{\partial x^2 \partial t^2} - R(C+3C')\frac{\partial \overline{u}_{\alpha\beta}(x,t)}{\partial t} + \\ &+ RC_m \frac{\partial^3 \overline{u}_{\alpha\beta}(x,t)}{\partial x^2 \partial t} = 0\end{aligned} \quad (1)$$

$$\begin{aligned}&\frac{\partial^2 u_o(x,t)}{\partial x^2} - (L+2M')C\frac{\partial^2 u_o(x,t)}{\partial t^2} \\ &+ (L+2M')C_m\frac{\partial^4 u_o(x,t)}{\partial x^2 \partial t^2} - RC\frac{\partial u_o(x,t)}{\partial t} + \\ &+ RC_m \frac{\partial^3 u_o(x,t)}{\partial x^2 \partial t} = 0\end{aligned} \quad (2)$$

that are representing, in complex and zero-sequence domain, the uncoupled models shown in Fig. 3.

3 The Simulation Model

3.1 The simulation of the Clarke model

In order to attempt the integration of the Clarke model shown in the previous paragraph, we are proposing a method of integration based on the theory of two ports.

At first, we notice that the model can be considered as linear; if that is not the true for the total model, it is the true for every single elementary cell; so it is possible to consider