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Dynamic phasors modeling of inverter fed induction generator

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ABSTRACT

Decentralized generation and microgrids are more common in new electric power systems, where each day there is more renewable energy generation from technology such as wind energy conversion systems and photovoltaic systems, connected to the power system through electronic converters and Flexible AC Transmission Systems (FACTS) that are implemented in the whole system to guarantee the stability and the quality of electric parameters. Some of these subsystems operate in continuous mode and others in discrete mode. It is very important develop models of these technologies so that their dynamics can be analyzed in both short and long periods of time. Individual aspects, such as induction generation, are modeled with dynamic phasors technique with good results. This work presents modeling and dynamical analysis of an induction generator, which is excited by a 3-phase inverter, using the dynamic phasors technique. These models are improved here by introducing the effect of electronic converter harmonics in the model and the dynamic analysis and its effect on the calculation of active and reactive powers. The first model considers the fundamental frequency for currents and voltages, with the DC component and second-order harmonic for rotor speed; this allows observation of the oscillating mechanical behaviors in the machine's speed and torque. Later, including the first and *k*th harmonic introduced by commutations of the inverter, allowing analysis of oscillating dynamics of the system's electrical variables such as voltages and currents. Also, new equations are presented for calculation of active and reactive powers based on dynamic phasors, which permit knowledge of average and main distorting powers.

1. Introduction

Scientific and technological advances in materials science, power electronics and other research areas, are allowing increased penetration of renewable energies such as wind and photovoltaic systems [1], thus strengthening the distributed generation, mainly by the characteristics of these resources and technologies, which can be integrated into microgrids[1] and operate individually or networked with other microgrids, sharing energy. Some important characteristics of the elements of these microgrids are that they are of different nature, either continuous time operation (generators, distribution grid, loads, etc.) and discrete time operation (electronic converters, power switches, loads, etc.), and they work at different frequencies. Thus it is important develop mathematic models that allow a dynamical analysis of the microgrid's subsystems for the purpose of analyzing electromagnetic transients of short duration and electromechanical transients of large duration.

Two traditional types of models exist for these elements. One is based on the Electromagnetic Transient Program (EMTP), where the models are quite detailed and are used to analyze fast electromagnetic transients with an integration step of the order of microseconds, obtaining very good accuracy in the results. Thanks to the availability of restructured EMTPs such as computer codes – for example, EMTP-RV [2,3] – and development of multi-core computing architectures, it is possible to perform a detailed simulation of power electronic systems, showing their commutation dynamics. For example, in [4] a microgrid is modeled and simulated to analyze its operation and power quality. Other models are based on the Transient Stability Program (TSP) where usually fast dynamics are neglected, because simulations are made at fundamental frequency, so they are known as phasors model. Thus requiring larger integration steps, on the order of milliseconds, are used for the analysis of transient stability caused by electromechanical phenomena. However, these 2 approaches have the following limitations: EMTP requires extensive computational effort when a complex system is simulated and TSP has a lack of accuracy when a fast transient electromagnetic occurs.

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[1] In this work the microgrids under analysis are formed by little micro-sources of order of few KW, integrated in low voltage three phase distribution systems, e.g. 220–400 Vac, where electrical parameters like powers, voltages and currents are regulated by PI controllers.

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List of symbols

Dynamic phasors symbols

$x(\tau)$	complex time domain waveform
$X_k(t)$	kth time varying Fourier coefficient
k	set of selected Fourier coefficients
ω_s	fundamental frequency of the system
T	period time of a cycle
j	imaginary operator

Inverter symbols

R	resistive load
C	capacitor
V_{dc}	direct current voltage
$V_{a,b,c}$	3-phase voltages
$V_{d,q}$	direct and quadrature voltages

IG symbols

R_s, R_r	stator and rotor resistances
L_s, L_r, L_m	stator, rotor, and mutual inductances
V_{dqs}, V_{dqr}	direct and quadrature stator and rotor voltages
i_{dqs}, i_{dqr}	direct and quadrature stator and rotor currents
λ_{dqs}, λ_{dqr}	direct and quadrature stator and rotor magnetic fluxes
J	inertia constant
P	number of pole pairs
B	viscous friction coefficient
T_L	mechanical load
$a_{i,j}$, b_i	constant parameters
ω_r	electrical rotor speed

Therefore, it is important to have a tool that can accurately and efficiently simulate both transients, taking into account the continuous-discrete hybrid nature of the elements [5]. The dynamic phasors (DP) modeling technique addresses this need [6] and is based on complex Fourier coefficients; where considering a small number of harmonics in the models is sufficient to obtain a good approximation of the dynamics of the variables.

So, as it is mentioned, the main differences in these three models, EMTP, TSP and DP are the frequency at they are simulated, and therefore, the time integration step. DP models are faster than EMTP models, because the time integration step is larger, but a condition must be applied, this is we need to work at a fundamental constant frequency (e.g. $f = 50$ Hz), and take into account some few harmonics. This is a restriction, but offers some powerful utilities, like we shall see in this paper.

The dynamic phasors modeling technique had its origins in modeling power electronic systems such as boost and buck converters [7–9]. Another area of widespread application is in FACTS [10–15], where power quality analysis is studied for the static VAR compensator (STATCOM), series resonant converters, dynamic voltage restorers, unified power flow controllers, thyristor-controlled series capacitors, and high voltage direct current (HVDC) transmission systems. Modeling of induction machines in their various versions has taken some interest like in [5], where a comparative assessment is made on different models of the doubly fed induction generator: detailed model, at fundamental frequency, with dynamic phasors, and reduced-order dynamic phasors models. A model for a single-phase induction machine is developed in [16], where the model keeps first harmonic for currents and DC component and the second harmonic for speed. In this work a small signal analysis is done, where eigenvalues are obtained for the ninth-order and seventh-order reduced models. In [17] a dynamic phasors model is obtained for a 3-phase induction motor and for a permanent magnet synchronous machine. In the first case, the transient dynamic with unbalanced voltages is explored experimentally and numerically. These two previous works consider that induction machine is directly connected to the voltage source, however at present the induction generators used in wind turbines are connected to the network through electronic converters, which allow optimize the extraction and conditioning of power generated. Dealing with the modelization of the converter is not a trivial task and different levels of detail may be achieved doing some assumptions. For example, in [18] it is assumed that the switching frequency is high enough to assume that the high-frequency components of the voltage signals generated by the inverters are totally filtered by the system and also that the switching energy losses can be neglected. However, this consideration has its consequences, such as not considering the power losses at high frequency inverter operation and loss of data in the fast transients, which may affect the design of controllers and protection calculation [19]. The machine inverter is still controlled in order to regulate the both active and reactive stator powers with the PI controller and the two inverters are included in the simulations, but the high frequency powers are not taken into account.

Recently in [15], the authors modeled a system consisting of a photovoltaic panel and a boost converter that included the time constant of the micro-source in the electronic converter dynamic, this allowed analysis of interactions between systems gave rise to oscillations that could lead to instability. In other work such as [8], both elements – induction machine and inverter – are considered, but the converter is modeled with the SSA technique, neglecting the switching frequency of the power electronics and the interaction that it can have with the micro-source.

A key consideration of the dynamic phasors approach is that the kth Fourier coefficients are used to obtain an accurate analysis. For example, in some applications $k = 1$ is selected when the fundamental frequency is dominant, as currents and voltages for induction machines; $k = 0, 2$ may be selected for mechanical speed and DC–DC converters, where the DC component describes the dynamics of the original signal very well and the second harmonic provides further information on the oscillatory dynamics. Choosing $k = 1$, 3, and 5 allows analysis of specific harmonic content presented in the system.

In summary, in previous works the following three cases are observed: (1) elements are modeled separately, so that no analysis is done of their interaction; (2) a work shows the interaction between a converter and microsource, however, the source produce direct current, so that there is no interaction at different frequencies and (3) both the induction machine and the converter are modeled at the fundamental frequency, so not reflect the rapid dynamics introduced by the inverter switching frequency. This paper uses the dynamic phasors technique to develop 2 models of the induction machine that is fed by a 3-phase inverter. The first model can reveal electromechanical oscillations of the rotor speed and torque under unbalanced voltages, considering $k = 1$ for electrical variables and $k = 0, 2$ for mechanical variables. The second model considers further utility the $k\text{th} = 45$ harmonic, where the oscillations introduced by the effects of inverter switching in the electrical variables such as voltages and currents can be analyzed for control design and protection schemes. Equations are also established for calculating active and reactive powers at different frequencies based on Fourier coefficients.

2. Outlines of the dynamic phasors approach

As is presented in [6] and commented in [20], dynamic phasors technique is based on four basic Eqs. (1–4):