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Analysis and control of induction generator supplying stand-alone AC loads employing a Matrix Converter

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ABSTRACT

This paper proposes a Capacitor Excited Induction Generator (CEIG)-Matrix Converter (MC) system for feeding stand-alone AC loads. The variable output voltage magnitude and frequency from CEIG is converted into a constant voltage magnitude and frequency at the load terminals by controlling MC using Space Vector Modulation (SVM) technique. This single-stage MC is turned up as a good alternative for the proposed system against commonly used AC/DC/AC two stage power converters. The configuration and implementation of the closed-loop control scheme employing dSPACE 1103 real time controller have been fully described in the paper. The proposed closed-loop controller regulates the AC load voltage irrespective of changes in the prime mover speed and load. A method for predetermining the steady-state performance of the proposed system has been developed and described with relevant analytical expressions. The effectiveness of the proposed system is exemplified through simulation results for various operating conditions. The proposed control technique is further validated using an experimental setup developed in the laboratory.

1. Introduction

The stand-alone power generation system is being considered as a feasible alternative to grid supply to power remote areas. This has become essential in growing economies where installing power lines to such locations has become uneconomical. Exploitation of locally available renewable or alternate energy resources such as wind, small hydro and biomass is an added attraction to establish such stand-alone systems. Among these renewable energy sources, wind energy will contribute to the considerable amount of electric power generation if it is installed in moderate/high wind potential areas.

Squirrel-cage induction machines are extensively employed for power generation from wind energy due to simple and rugged rotor construction, low cost, almost nil maintenance and generator operation without the need of DC supply [1–2]. To operate squirrel-cage IM as a generator, a suitable value of excitation capacitor has to be connected at the stator terminals [3–4]. This configuration of operating the IM as a generator is termed as Capacitor Excited Induction Generator (CEIG). For a given excitation capacitor bank, the output voltage magnitude and frequency of the CEIG vary depending upon the rotor speed and load at the stator terminals. Certain frequency insensitive loads which work safely with a voltage of variable magnitude can use this AC power as such. For applications requiring a controllable DC supply, in the beginning stages of development, conventional three-phase controlled rectifiers were used [5].

For applications requiring a controllable AC supply, many configurations are proposed in the literatures [6–14]. In this context, Ahmed et al. have developed dead beat current controller for a voltage source converter and vector controlled variable speed three-phase squirrel cage induction generator with phase locked loop for regulating AC and DC voltages. In this scheme, a DSP is used for implementation of the close loop control to operate the converter for maintaining constant AC as well as DC voltages [9]. Senthilkumar et al. have developed close loop control scheme for wind-driven induction generator system employing diode bridge rectifier-inverter for supplying stand-alone AC loads. This scheme requires the battery bank to be connected between three-phase Diode Bridge Rectifier (DBR) and the inverter for maintaining

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Nomenclature

a	per unit frequency = f_g/f_r
b	per unit speed = N/N_s
C	per phase excitation capacitance, F
q	voltage transfer ratio
E	per phase air-gap voltage, V
v_{AB}, v_{BC}, v_{CA}	Instantaneous line voltages at the input terminals of the MC, V
v_{ab}, v_{bc}, v_{ca}	Instantaneous line voltages at the output terminals of the MC, V
V_{ML}, V_{MP}	rms line and phase voltage at the matrix converter output terminals, respectively, V
I_s	line current of stator, A
P_g	generator output power, W
P_L	AC load power, W
R_1, X_1	per phase resistance and per phase leakage reactance of the stator, respectively, Ω
R_2, X_2	rotor per phase resistance and per phase leakage reactance (as referred to stator), respectively, Ω
X_m	per phase magnetizing reactance, Ω
R_e	generator terminal per phase equivalent resistance corresponds to AC loading, Ω
V_{gL}, V_{gP}	line and phase voltage at the generator terminals, respectively, V
Z	per phase equivalent circuit loop impedance, Ω
f_g	generator frequency, Hz
f_r	rated frequency, Hz
R_L	load resistance per phase, Ω

power balance [10]. Jayaramaiah and Fernandes have proposed voltage and frequency controller for SEIGs with one hysteresis current controller and two PI controllers. Current controlled voltage source inverter is employed in this scheme and this scheme requires a start-up battery [11]. In all these schemes for supplying stand-alone AC loads from CEIG, two/three power converters stages are employed along with energy storage elements such as inductor and electrolytic capacitor.

With the advent of power electronic technology and fast acting digital controllers, researchers have shown tremendous interest in developing new power electronic topologies for improved performance [15–18]. In this context, MC is proposed in energy converting systems due to compact design and elimination of bulky capacitor and inductor. Considering these advantages, an attempt has been made in this paper by employing MC to supply stand-alone AC loads from a variable voltage source i.e. output of CEIG. MC is turned up as a good alternative for the proposed system against commonly used AC/DC/AC two-stage power converters. Independent control of the output voltage magnitude, frequency and phase angle as well as the input power factor is the added advantage of employing the MC for the proposed wind energy conversion system.

The closed-loop control scheme for maintaining the required load voltage magnitude and frequency has been developed for the proposed system and implemented using a dSPACE 1103 real time controller board. The space vector pulse width modulation technique is employed to generate modulating functions as well as gating signals to the power switches in the MC. The other objective of the proposed controller is to maintain unity displacement power factor at the MC input terminals. This reduces the burden on the excitation capacitor by supplying only the reactive power needed for the CEIG. The procedure for the predetermination of the performance of the proposed CEIG-MC system has been developed employing Particle Swarm Optimization (PSO) technique. The simulation results using Matlab/Simulink model of the CEIG-MC system along with the experimental ones under various operating conditions are given in the paper to support the usefulness of the present proposal. A detailed configuration of the proposed system, its analysis, derivation of equivalent resistance for representing the MC supplying AC loads at the CEIG terminals are presented in the succeeding sub sections.

2. Proposed CEIG-MC system

The complete structure of the proposed system is given in Fig. 1. It consists of a prime mover which drives the CEIG, a MC and direct Space Vector Modulation (SVM) based control scheme. Here, the output of CEIG is connected to the MC input terminals and the AC load is connected across the MC output terminals. The line voltages and line currents of the stand-alone AC load and voltages of the CEIG are fed to the SVM based closed-loop controller through suitable sensors.

The modulation index of the MC is adjusted in a closed-loop to maintain the desired voltage magnitude at the load terminals. The load voltage is properly scaled down and filtered for giving feedback signals to the controller. The entire closed-loop control strategy has been developed by using dSPACE 1103 based real time digital controller board. The steps involved in the calculation of rms value of voltage are given in reference [10]. The error i.e. output of the summer is given to the digital PI controller which gives the modulation index (q), through which voltage at the MC output terminals is maintained constant. The virtually generated unit peak sinusoidal signal (50 Hz) is multiplied by the control signal (i.e., modulation index) to generate the modulating signal. This modulating signal is given to the SVM to generate gating pulses for the IGBTs in MC. The PWM signals from dSPACE 1103 board are amplified by ULN 2003 IC and given to the MC gate driver circuit.

3. Control strategy for matrix converter

Matrix converter (MC) consists of $m \times n$ bidirectional switches connecting directly the ‘m’ phase power supply to the ‘n’ phase load and providing single stage AC/AC conversion [19–20]. For the proposed system, MC consists of 3×3 bidirectional switches (BDS). Connection of any of the input phases (A, B and C) to any of the output phases (a, b and c) can be made with the appropriate control of these switches shown as in Fig. 1. With the nine BDS, 512 (2^9) different switching states are possible for the MC. These switching states are reduced to 27 (3^3) by considering constraints, namely, (i) the input phases should never be shorted and (ii) the output phases should never be opened.

Various control strategies are available in the literature for operating MC fed with constant AC voltage source [21–23]. Among various control techniques, SVM algorithm possesses the following advantages as compared to the other modulation techniques: (i) it provides a maximum voltage ratio of 0.866, (ii) it reduces the number of switch commutations in each cycle period, (iii) it is easy to implement, and (iv) it is easy to operate under unbalanced conditions. Further, SVM algorithm has the capability to control input current vectors and output voltage vectors independently [23]. Hence SVM technique has been chosen in the work for controlling MC.

In SVM technique, selection of valid MC switching states and calculation of corresponding on-time durations are needed to con-