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A MATRIX CONVERTER CONTROLLED INDUCTION GENERATOR FOR SUSTAINING CONSTANT VOLTAGE AND FREQUENCY USING SVM

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Abstract-This paper recommends a Matrix Converter (MC) fed Capacitor Excited Induction Generator (CEIG) - system for feeding stand-alone AC loads. By controlling matrix converter using space vector modulation technique variable frequency and magnitude of the variable output voltage from capacitor excited inductor generator is converter into constant frequency and constant output voltage at the load side. This single-stage Matrix converter is turned up as a virtuous substitute for the proposed system beside ordinarily used two stage power converters. Regardless of the speed of the prime mover and type of load the projected closed-loop controller controls the AC load voltage. Ascheme for predetermining the steady-state performance of the proposed system has been established and designated with appropriate systematic expressions. The effectiveness of the proposed system is demonstrated through simulation results for numerous operating conditions.

Keywords:Matrix converter, Induction generator, space vector modulation

I.Introduction

An induction generator or asynchronous generator is a kind of alternating current (AC) electrical generator that customs the principles of induction motors to yield power. Induction generators function by mechanically revolving their rotors quicker than synchronous speed. A systematic AC asynchronous motor typically can be used as a generator, without any interior alterations. Induction generators are beneficial in applications such as tiny hydro power plants, wind turbines, or in tumbling high-pressure gas streams to lower pressure, since they can recuperate energy with comparatively modest controls.

An induction generator typicallypulls its excitation power from an electrical grid; occasionally, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot customarily "black start" a de-energized distribution system. An induction machine entails externally supplied armature current. Because the rotor field constantly lags behind the stator field, the induction machine continuously "consumes" reactive power, irrespective of whether it is operating as a generator or a motor. A source of excitation current for magnetizing flux (reactive power) for the stator is still obligatory, to persuade rotor current. This can be abounding from the electrical grid or, once it starts fabricating power, from the generator itself. An induction machine can be underway by charging the capacitors, with a DC source, while the generator is rotating typically at or beyond generating speeds. Once the DC source is detached the capacitors will deliver the magnetization current required to initiate creating voltage.

Steady-state analysis of the proposed system

In the stand-alone operation of CEIG, stator voltage magnitude and frequency will vary with prime mover speed, capacitor value and load parameter. Hence, the steady-state equivalent circuit of three phase induction machine has been suitably modified toinclude this variable nature of frequency and the resultant equivalent circuit is shown in Fig. 2 [25–26]. In this circuit all the parameters are divided by a so that the magnetisation characteristic (E/avsXm), and reactance value of the machine, capacitance and load obtained at rated frequency can be used for the steady-state analysis. For the circuit shown in Fig. 1, the loop impedance, Z can be written as

$$Z = \left\{ \left[\frac{R}{a}\right] ll^{el} \left[\frac{-jX_C}{a^2}\right] \right\} + \left\{ \frac{R1}{a} + jX_1 \right\} + \left\{ jXm ll^{el} \left[\frac{R2}{a-b} + jX_2\right] \right\}$$

Since no voltage is applied to the stator, only rotor residual magnetism causes emf to build in the CEIG.

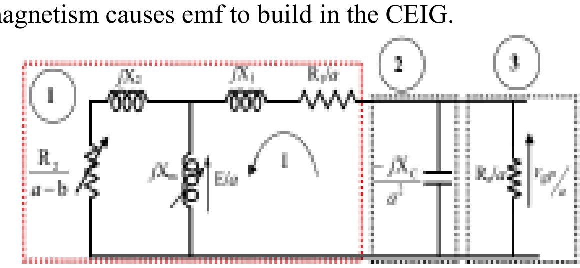

Fig. 1. Equivalent circuit of the capacitor excited inductor generator connected to load

So, referring to Fig. 1, for any operating point, there will be a load voltage and also voltage across individual circuit components, but the net loop voltage will be zero. Hence, if Z is net complex loop impendence as given in (8) and I is loop current shown in Fig. 2, then the product of I and Z can be equated to zero i.e., IZ = 0. Since the current, I has to be finite value at any steady-state operating point, only the value of Z has to be zero. This is possible because Z encompasses of inductive and capacitive reactances and positive and equivalent negative value {i.e., R2/(a-b)} of

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resistances. For the circuit shown in Fig. 2, the values of a, b and Xm are unknown and the remaining parameters are known and assumed to be constant for carrying out the steady-state analysis of CEIG. So, the first step in steady-state analysis of CEIG is to determine these unknown parameters for a given operating condition,namely, for a given value of b, excitation capacitor and load parameters along with the machine parameters. To determine these unknown variables, the real and reactive parts of (8) are separately equated to zero and then going through a lengthy derivation, a polynomial in p.u. frequency is obtained when p.u. speed (b) is taken as the known parameter [25–26]. Then, this polynomial has to be solved by adopting some numerical methods to obtain aandXm. Recently, much simpler methods have been proposed by a few authors for the analysis of CEIG by making use of optimization techniques [26–29]. The advantage of such methods is that the loop impedance given in (8) can be taken as it is and solved straightaway without any lengthy derivation or simplifications [26–29]. In this paper PSO technique is employed to arrive at the values of aandXm for a given value of b, machine, excitation and load parameters by taking loop impedance as the objective function.

$$f(a, X_m) = abs(Z)$$

where Z is given in (8). It is to be noted that the final value of the objective function will be made to zero through PSO technique. Hence, the values, namely, aandXm obtained will be unique for any operating conditions using this technique. After obtaining the values of aandXm for a given value of b by PSO technique, the induced emf can be determined from the E/a VsXm characteristics of CEIG. Then, using the equivalent circuit shown in Fig. 1, the load voltage and power output from CEIG can be calculated as [26]

$$V_{gP} = \left\{ \frac{R_L^2 + X_L^2}{\{(R_1/a) + R_L\}^2 + (X_1 - X_L)^2} \right\}^{1/2} E$$

$$I_P = V_{gP}/R_e \quad \text{and} \quad P_e = 3V_{gP}I_P$$

Where

$$R_L = \frac{R_e X_C^2}{a[a^2 R_e^2 + X_C^2]} \text{ and } X_L = \frac{R_e^2 X_C}{[a^2 R^2 + X_C^2]}$$

It can be noted from (8), (10) and (11), the effective value of resistance, Re at the generator terminals is required for carrying out the steady-state analysis. So, the power supplied to the stand-alone AC load through MC should be appropriately reflected at the output terminals of the generator and the procedure for obtaining this equivalence is described in the next sub-section.

II. Proposed CEIG-MC System

The complete structure of the proposed system is given in Fig. 2. It consists of a prime mover which drives the CEIG, a MC and direct Space Vector Modulation (SVM) based control scheme. Here, theoutput 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.

Control strategy for matrix converter

Matrix converter (MC) consists of m×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 construct the required three-phase output voltage.

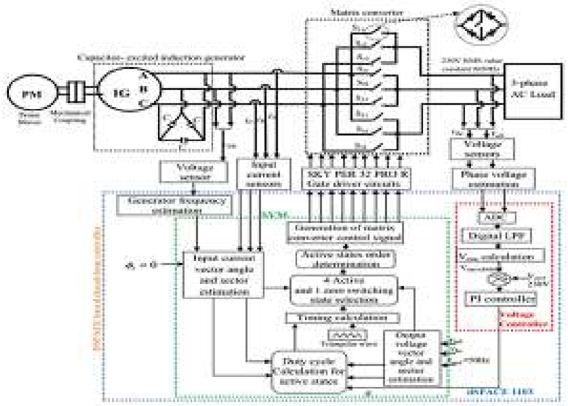


Fig. 2. Schematic diagram of stand-alone matrix converter controlled induction generator

Self-excitation process of CEIG

It is known that the generator will stay in self-excitation for a given load and speed only within a given range of terminal capacitance i.e., between the minimum and maximum (Cmin and Cmax) values [30–32]. At these two boundary values, the magnetizing reactance of the generator will reach the highest value called critical magnetizing reactance (Xmc). For a given machine, the two values of XC corresponding to Cmin and Cmax can be obtained for a given per unit frequency, a. Then, using the base frequency (i.e., 50 Hz in the present case), the value of capacitances, Cmin and Cmaxcan be calculated. For the chosen 230 V, 3.7 kW, 4-pole, 50 Hz squirrel-cage induction machine, Cmin and Cmax were calculated as 94 lF and 555 lF respectively. The maximum value of excitation capacitance, Cmax would result in higher level of saturation, which results in overloading the generator due to the excitation capacitorcurrent alone. Hence, the excitation capacitance will be chosen close to the lower boundary i.e., Cmin. In the present case, the value of excitation capacitance is chosen as 100 mF per phase so that the machine delivers the rated power at rated speed, which also guarantees the voltage stability of generator. A DC motor was used as a prime-mover to set any required speed of operation. To show the successful voltage build-up of CEIG, with the 100 mF capacitor, generator rotated at 1500 rpm using DC motor and then the excitation capacitor bank was closed. Fig. 3.Shows the MATLAB and simulated results of instantaneous values of the stator voltage and current.

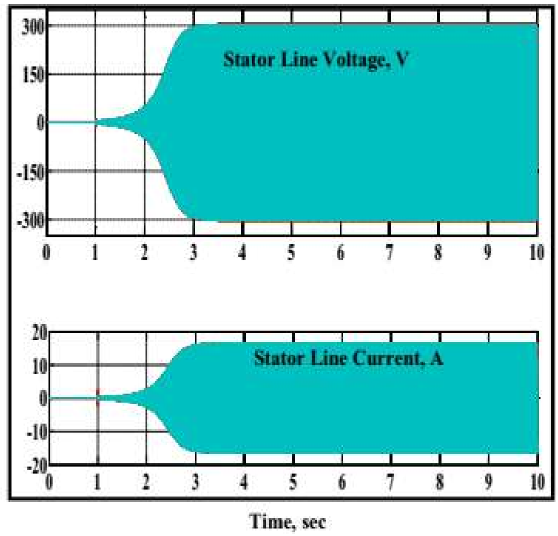


Fig. 3. Stator side line voltage and current

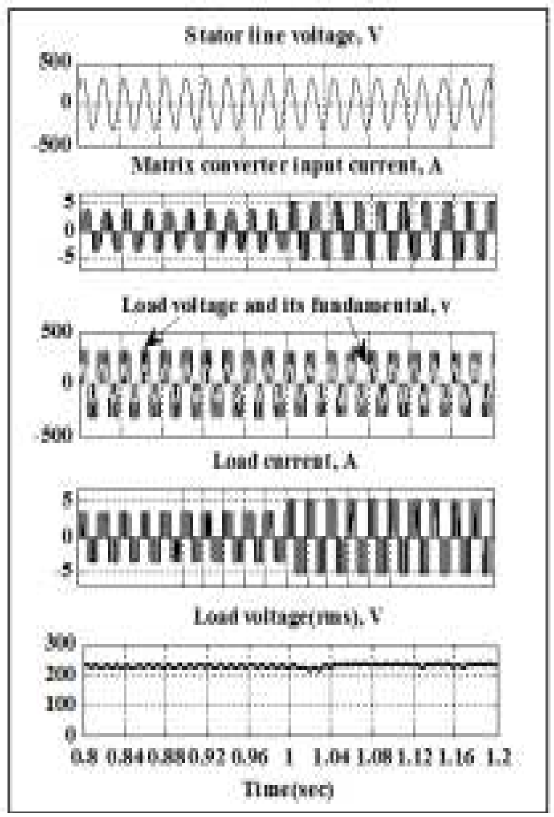


Fig. 4.Dynamic response to step change in load C = 100 mF, N = 1500 rpm. a) t_{lc}: instant at which load change initiated from 0.88 kW to 1.3 kW

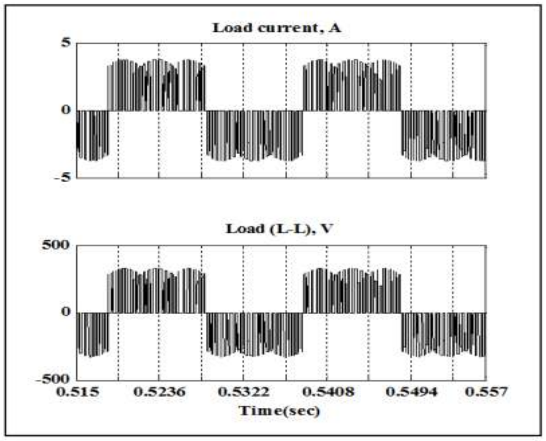


Fig. 5.Dynamic response to step change in load C = 100 mF, N = 1500 rpm. b) Simulation waveform for load current and load voltage for PL = 0.88 kW

III. Results and discussions

To show the efficacy of the developed controller, simulation results have been conducted for various operating conditions and these results are discussed along with predetermined values in the following sub-sections.

Steady-state operation

Simulation have been conducted on the proposed CEIG-MC system supplying constant load power by operating the generator with different rotor speeds and the results are given in Fig. 5. The load voltage has been maintained at 230 V ± 2% by dSPACE based closed-loop controller. The calculated values using the predetermination procedure described in Section 4 are also given in the figure. It can be seen from Fig. 5 that the stator voltage reduces with speed for a given load and the operating speed range decreases with increase in load power. To keep that load constant, the input current to the MC increases with the reduction of speed. Generator comes out of excitation, if speed is reduced below certain value and hence constant power cannot be supplied below some value of speed with fixed excitation capacitor. Simulation have also been conducted on the proposed system for supplying variable load power by operating the generator with a constant speed of 1500 rpm. In this experiment also the load voltage is maintained at 230 V and results are furnished in Fig. 6 along with the predicted values.

It can be seen from this figure that the stator voltage reduces with increase in load. Despite constant rotor speed, frequency decreases with increase in output power. This shows that the generator frequency of CEIG not only depends on the rotor speed but also depends on the load, excitation capacitor and machine parameters. This figure also gives the variation of load power, equivalent resistance (Re), magnetizing reactance and stator line current with matrix converter input current. The performance of the proposed system has been examined for supplying the constant load power with different set values of AC load voltages for a constant speed operation. Table 1 shows the performance of the system for three different load voltages, namely, 250 V, 230 V and 210 V for two different load settings at 1500 rpm. Interestingly system performance is same for given speed and load power with different load voltages. This is due to the fact that the equivalent load resistance, Re for these settingsturns out to be same. For example, for PL = 1 kW, predetermined value of Re is 208 X for any load voltage settings.

Dynamic performance

To validate the successful working of the proposed system and closed-loop controller, simulation and simulations have been carried out for certain step change in load, speed and reference output voltages. In each case simulationly recorded waveforms of stator line voltage, MC input current, load voltage (and its fundamental), load current and rms value of load voltage along with the simulated waveforms are presented.

(i) Performance without filter

Fig. 7 shows the simulation and simulated waveforms for step change in load from 0.88 kW to 1.3 kW. For this experiment, generator was run at 1500 rpm with per phase excitation capacitance of 100 mF, reference voltage and frequency were set at 230 V, 50 Hz respectively. It can be observed from this figure that the stator terminal voltage decreases from 234 V to 229 V with increase in MC input current from 2.4 A to 3.6 A for step change in load. Further, MC supplies 2.2 A at 0.88 kW and it increases to 3.4 A when the load was increased to 1.3 kW and closed-loop controller maintains 230 V, 50 Hz at the load terminals.

Fig 8b shows the enlarged view of load voltage and load current waveforms for a load of 0.88 kW. Simulation have been conducted for step change in speed from 1300 to 1500 rpm for a constant load of 1.2 kW and the results are given in Fig. 8 along with the corresponding simulated results. In simulation set up, speed of prime mover i.e. separately excited DC motor was changed by suddenly decreasing its field current. From this figure it can be observed that stator terminal voltage increases from 215 V to 234 V and frequency increases from 42.08 Hz to 49.23 Hz with increase in speed but controller maintains load voltage and frequency constant at set values i.e., 230 V, 50 Hz. MC input current decreases from 3.5 A to 3 A to supply this constant power i.e., 1.2 kW. To check the effectiveness and robustness of the controller, simulation have been conducted for step change in reference load voltage (rms). Initially load voltage reference was set at 230 V and this value was suddenly changed to 200 V by keeping the rotational speed at 1500 rpm with the load frequency of 50 Hz. From Fig. 9, it can be noted that the closed-loop controlleroperates successfully for tracking these set values of load voltages with in a cycle and maintains the frequency at 50 Hz for both of the settings. This shows the independent control of voltage magnitude and frequency of the proposed CEIG-MC system. The simulated results for this operation are also given in Fig. 9.

(ii) Performance with filter

The performance of the system has also been studied with filters as shown in Fig. 10. For simulation, L = 2mH and C = 2 mF have been used for input filter and these values are 10mH and 5 mF for output filter. Simulation has been carried out for different operating conditions and for the sake of brevity, results are given in Fig. 11 for step change in load. It can be noted from this figure that the voltage and currents at various points are sinusoidal as compared to without filter given in Fig. 7. Fig. 12 shows the load current wave form and corresponding THD with and without filter. So, by using a very small value of filter components, the THD can be reduced to very low value and this value is within the acceptable limit as per the harmonic standards.

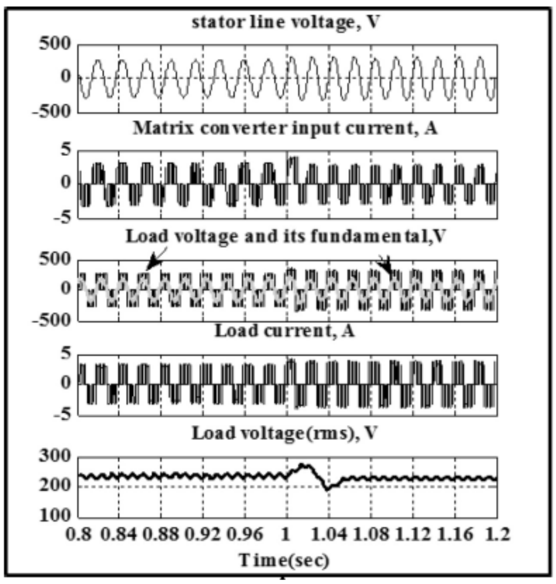


Fig.6. Dynamic response to step change in reference voltage (VML) from 230 V to 200 V, C = 100 mF, N = 1500 rpm, PL = 1.2 kW, tcr: instant at which change in reference voltage initiated.

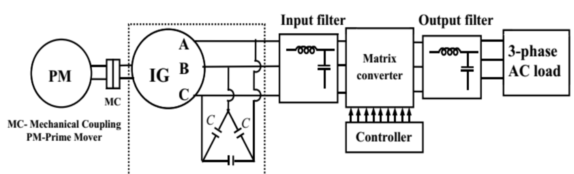


Fig. 7.Schematic of the proposed stand-alone CEIG-MC system with filters.

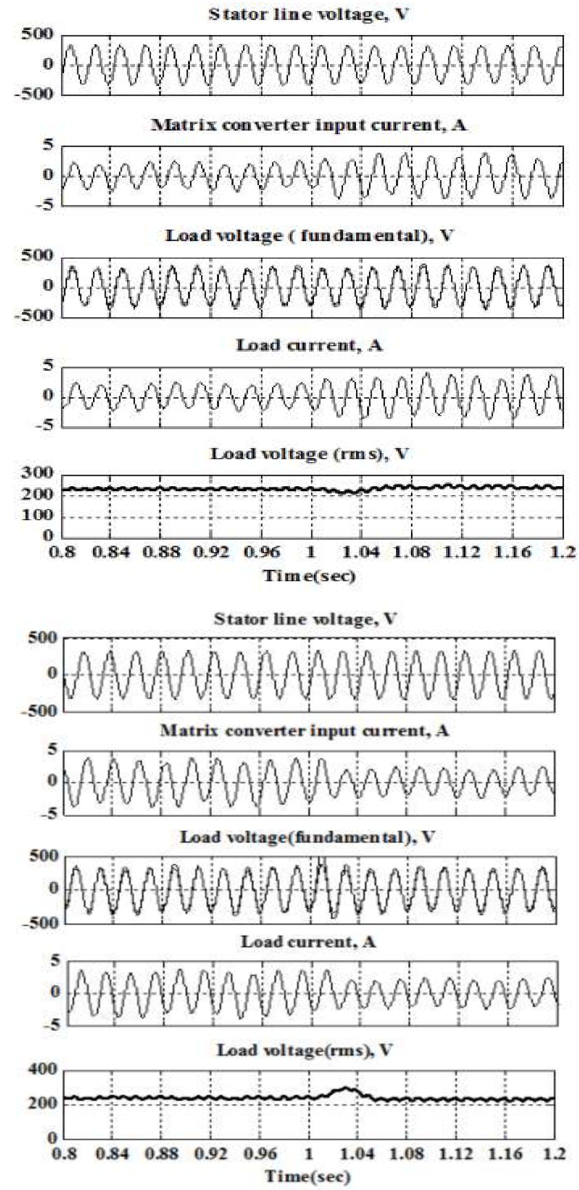
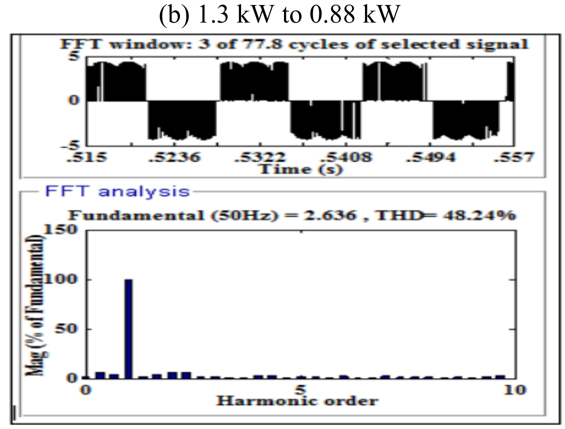


Fig.8. Dynamic response to step change in load with filters. C = 100 mF, N = 1500 rpm, tlc: instant at which load change is initiated from (a) 0.88 kW to 1.3 kW and (b) 1.3 kW to 0.88 kW



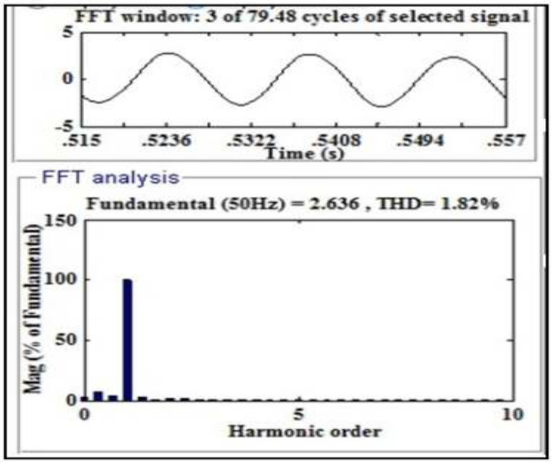


Fig.9. Load current waveform and its Harmonic spectrum (a) without filters and (b) with filters. N = 1500 rpm, C = 100 mF, PL = 1.2 kW and VML = 230 V, 50 Hz.

IV. Conclusion

The working of a stand-alone system of CEIG supplying AC loads through Matrix Converter (MC) operated with Space Vector Modulation (SVM) control scheme has been studied. The self-excitationand reactive power support for the IG of the proposed system are obtained by connecting AC capacitors at the stator terminals of the induction machine. A closed-loop controller has been developed employing SVM technique for maintaining the set value of voltage and frequency at the stand-alone load terminals irrespective of rotational speed of induction generator and the value of load. It is simple to set the input power factor of the MC to any desired value with SVM technique. Hence, to have the reduced burden on the excitation capacitor banks, the input displacement power factor of the MC is maintained at unity by this technique. This makes the effective load (i.e., MC along with the load) at the generator terminal as the only resistance (Re). The procedure for the calculation of this equivalence has been described in the paper. The SVM based closed-loop controller has been implemented using dSPACE 1103 real time controller board. A systematic approach has been developed for the analysis of CEIG-MC system supplying stand-alone AC loads. This approach involves steady-state equivalent circuit of CEIG and PSO technique.

The proposed system was also simulated using MATLAB/Simulink toolbox for the transient analysis. Simulated results on the various performance quantities along with the predetermined performance characteristics confirm the successful working of the developed controller and usefulness of the proposed system. It is to be noted that the present stand-alone CEIG-MC system will have the voltage harmonics at the AC load terminals and current harmonics at the generator terminals. Hence an appropriate filter circuits are essential for improving the quality of the waveform. These aspects are also discussed in the paper. To show the efficacy of the proposed control strategy and successful working of the proposed system, complete simulationsetup was assembled in the laboratory. The prototype system has been tested in various steady-state and transient operating conditions. The results obtained from simulation set-up with a 3- phase delta connected, 230 V, 50 Hz, 3.7 kW IG show the effectiveness of the proposed system to regulate the load voltage at the setvalue irrespective of changes in prime mover speed, and load. A close agreement between thesimulation and predetermined characteristics demonstrates the successful working of the system and validates the method developed for the performance predetermination.

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