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A Voltage and Frequency Controller for Stand Alone Pico Hydro Generation

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ABSTRACT

This paper deals with a voltage and frequency (VF) controller for an isolated power generation system based on an asynchronous generator (AG) driven by a pico hydro turbine. The proposed controller is a combination of a static compensator (STATCOM) and an electronic load controller (ELC) for decoupled control of the reactive and active powers of the AG system to control the voltage and frequency respectively. The proposed generating system along with its VF controller is modeled in MATLAB using SIMULINK and PSB (Power System Block Sets) toolboxes. The performance of the controller is verified for the proposed system and feeding various types of consumer load such as linear/non-linear, balanced/unbalanced and dynamic loads.

Keywords: Isolated Asynchronous Generator, Voltage and Frequency Controller, Uncontrolled Pico Hydro Turbine, Dynamic Load

1. Introduction

Asynchronous cage machines (AMs) are robust, inexpensive compared with DC and wound field synchronous machines, require little maintenance, and have high power weight ratio[1-3]. Despite these favorable features, commercialization of an asynchronous machine as an isolated asynchronous generator (IAG) is still a bottleneck because of its unsatisfactory voltage and frequency regulation, even when driven at constant speed and feeding varying loads. In view of this, a number of research publications are reported on modeling, steady state and transient analysis [1,2] of the capacitor excited asynchronous generator (CEAG) along with its controller [3-20]. In these applications, the pico hydro turbine is generally uncontrolled and hence provides constant power. Thus IAG has to operate at constant power at varying consumer loads, called "single point" operation, as the power, excitation capacitance and the speed are maintained nearly constant. Therefore for regulating constant power at the generator terminals, ELCs are used which in turn regulate voltage and frequency of the isolated generation. The basic principle of operation is that total generated power should be absorbed by consumer loads and ELCs to regulate power constant at the generator terminals. In the reported literature [6-13] for pico/micro hydro generation, variable VAR compensators are used to regulate the voltage with allowable frequency variation [6-8]. Moreover, there are some attempts which

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are based on turbine governor control[13] in pico hydro power applications. In later stage, the development of electronic load controllers[14-21] have been reported for maintaining constant power at the terminal of the generator.

In this paper, a new VF controller is proposed which is having capability of controlling the voltage and frequency in decoupled manner. For controlling the voltage, a static compensator (STATCOM) is used as a reactive power compensator along with harmonic eliminator and a load balancer while for controlling the frequency; an electronic load controller (ELC) is used to regulate the total active power at the terminals of generator. The STATCOM is realized using IGBTs (Insulated gate bipolar junction transistors) based voltage source converter (VSC), and a capacitor as an energy storage element at its DC link, while an ELC consists of a diode bridge rectifier, a chopper switch and an auxiliary load resistance.

2. System Configuration

Fig. 1 shows the system configuration of CEAG (capacitor excited asynchronous generator), DVFC (Decoupled voltage and frequency controller) (consisting 3 leg IGBT based VSC and diode bridge rectifier based ELC) and the consumer loads. The delta connected 3-phase capacitor bank is used for the generator excitation and value of an excitation capacitor is selected to generate the rated voltage at no load. The CEAG generates constant power and when consumer load power changes, the DC chopper of an ELC absorbs the difference in power (generated-consumed) into an auxiliary load, while STATCOM is used to regulate the voltage due to load changes. Thus generated voltage and frequency are not affected and remain constant during the changes in consumer loads.

The DVFC is an arrangement of a STATCOM with an ELC. STATCOM consists of IGBT based current controlled 3-leg VSC, DC bus capacitor and AC inductors. The output of the VSC is connected through the AC filtering inductors to the CEAG terminals. The DC bus capacitor is used to filter voltage ripples and provides self supporting DC bus. A DC chopper in an ELC is used to control the extra power in the controller auxiliary load due to change in consumer loads, so that generated power at the generator remains constant.

Fig.2 shows the control scheme of decoupled voltage and frequency controller (DVFC) for providing single point operation (constant voltage and frequency along with constant excitation capacitor) of CEAG.

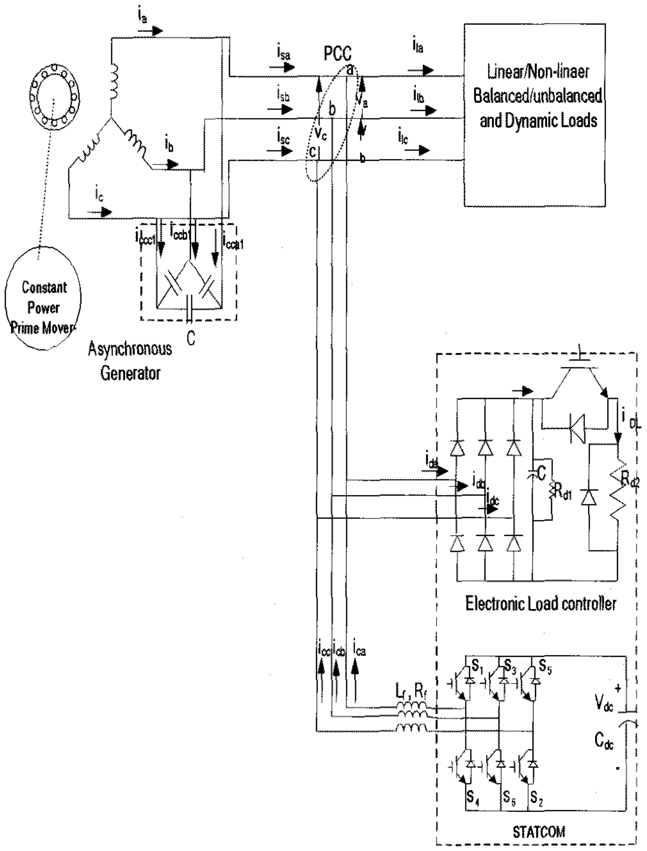

Fig. 1 Schematic diagram of a proposed VF controller for an isolated power generation

The control algorithm for STATCOM control is based on the generation of reference source currents while ELC is controlled for regulating the constant generated power.

3. Control Strategy

Fig.2 shows the control strategy of the proposed VF controller for CEAG. The control scheme of STATCOM to regulate the terminal voltage of the CEAG which is based on the generation of source currents has two components, in-phase and quadrature, with AC voltage.

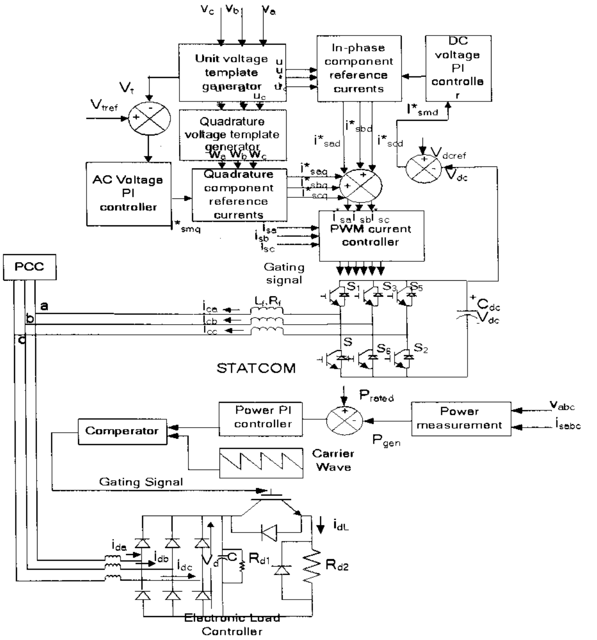

Fig. 2 Control scheme for the proposed voltage and frequency controller

The in-phase unit vectors (u_a, u_b and u_c) are three-phase sinusoidal function, computed by dividing the AC voltages v_a, v_b and v_c by their amplitude V_t. Another set of quadrature unit vectors (w_a, w_b and w_c) are sinusoidal function obtained from in-phase vectors (u_a, u_b and u_c). To regulate AC terminal voltage (V_t), it is sensed and compared with the reference voltage. The voltage error is processed in the PI (Proportional Integral) controller. The output of the PI controller (Ismq*) for AC voltage control loop decides the amplitude of reactive current to be generated by the STATCOM. Multiplication of quadrature unit vectors (wa, wb and wc) with the output of PI based AC voltage controller (Ismq*) yields the quadrature component of the reference source currents (isaq*, isbq* and iscq*). To provide a self-supporting DC bus of STATCOM, its DC bus voltage is sensed and compared with DC reference voltage. The error voltage is processed in another PI controller. The output of the PI controller (Ismd*) decides the amplitude of the active power component of the source current. The output of the PI controller (Ismd*) decides the amplitude of active power component of source current. Multiplication of in-phase unit vectors (ua, ub and uc) with output of PI controller (Ismd*) yields the in-phase component of the reference source currents (isad*, isbd*and iscd*). The instantaneous sum of quadrature and in-phase components gives the reference source currents (isa*, isb* and isc*), which are compared with the sensed source currents (isa, isb and isc). These current error signals are amplified and compared with the triangular carrier wave to generate the gating signals for VSC of STATCOM.

For controlling the chopper of an electronic load controller, measured power (Pgen) is compared with rated power (Pr) of the generator and then output of a power PI controller is compared with the saw-tooth carrier wave resulting in PWM output of varying duty cycle for switching of the IGBT of an ELC chopper.

4. Control Algorithm

Basic equations of control algorithm of a proposed decoupled VF controller (DVFC) for CEAG are given here. The control scheme is divided into two sections. Section 'A' describes the equations of controlling the "STATCOM" while section 'B' deals with the chopper control of an electronic load controller (ELC).

4.1 Control Algorithm for STATCOM

Different components of CEAG-DVFC system shown in Fig. 1 are modelled as follows.

Three-phase voltages at the CEAG terminals (v_a, v_b and v_c) are considered sinusoidal and hence their amplitude is computed as:

$$V_t = \sqrt{\{(2/3)\,(v_a^2 + v_b^2 + v_c^2)\}} \qquad (1)$$

The unit vector in phase with va, vb and vc are derived as:

$$u_a = v_a/V_t;\ u_b = v_b/V_t;u_c = v_c/V_t \qquad (2)$$

The unit vectors in quadrature with va, vb and vc may be derived using a quadrature transformation of the in-phase unit vectors ua, ub and uc as:

$$w_a = -u_b / \sqrt{3} + u_c / \sqrt{3} \qquad (3)$$

$$w_b = \sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \qquad (4)$$

$$w_c = -\sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \qquad (5)$$

4.1.1 Quadrature component of reference source currents

The AC voltage error Ver(n) at the nth sampling instant is:

$$V_{er}(n) = V_{tref}(n) - V_t(n) \tag{6}$$

where $V_{tref}(n)$ is the amplitude of reference AC terminal voltage and Vt(n) is the amplitude of the sensed three-phase AC voltage at the CEAG terminals at nth instant.

The output of the PI controller ($I^*_{smq(n)}$) for maintaining AC terminal voltage constant at the nth sampling instant is expressed as:

$$I^*_{smq}(n)=I^*_{smq}(n-1)+K_{pa}\{V_{er}(n)-V_{er}(n-1)\}+K_{ia}V_{er}(n) \tag{7}$$

where K_{pa} and K_{ia} are the proportional and integral gain constants of the proportional integral (PI) controller. $V_{er\,(n)}$ and $V_{er(n-1)}$ are the voltage errors in nth and (n-1)th instant and $I^*_{smq(n-1)}$ is the amplitude of quadrature component of the reference source current at (n-1)th instant.

The quadrature components of the reference source currents are computed as:

$$i^*_{saq} = I^*_{smq}\, w_a;\ i^*_{sbq} = I^*_{smq}\, w_b;\ i^*_{scq} = I^*_{smq}\, w_c \tag{8}$$

4.1.2 In-Phase Component of Reference Source Currents

A PI voltage controller is used to control the DC bus voltage of STATCOM to obtain in phase component of reference source currents.

The error in DC bus voltage of STATCOM ($V_{dcer}(n)$) at nth sampling instant is:

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \tag{9}$$

where $V_{dcref(n)}$ is the reference DC voltage and $V_{dc(n)}$ is the sensed DC link voltage of the STATCOM. The output of the PI controller for maintaining DC bus voltage of the STATCOM at the nth sampling instant is expressed as:

$$I^*_{smd(n)}=I^*_{smd(n-1)}+K_{pd}\{V_{dcer(n)}-V_{dcer(n-1)}\}+K_{id}V_{dcer(n)} \tag{10}$$

$I^*_{smd(n)}$ is considered as the amplitude of active component of source current. K_{pd} and K_{id} are the proportional and integral gain constants of the DC bus PI voltage controller.

In-phase components of reference source currents are computed as:

$$i^*_{sad} = I^*_{smd}\, u_a;\ i^*_{sbd} = I^*_{smd} u_b;\ i^*_{scd} = I^*_{smd}\, u_c \tag{11}$$

4.1.3 Reference Source Currents

Total reference source currents are sum of in-phase and quadrature components of the reference source currents as:

$$i^*_{sa} = i^*_{saq} + i^*_{sad} \tag{12}$$

$$i^*_{sb} = i^*_{sbq} + i^*_{sbd} \tag{13}$$

$$i^*_{sc} = i^*_{scq} + i^*_{scd} \tag{14}$$

4.1.4 PWM Current Controller

These reference currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with the sensed source currents (i_{sa}, i_{sb} and i_{sc}). The ON/OFF switching patterns of the gate drive signals to the IGBTs of VSC are generated from the PWM current controller. The current errors are computed as:

$$i_{saerr} = i^*_{sa} - i_{sa} \tag{15}$$

$$i_{sberr} = i^*_{sb} - i_{sb} \tag{16}$$

$$i_{scerr} = i^*_{sc} - i_{sc} \tag{17}$$

These current error signals are amplified and then compared with the triangular carrier wave. If the amplified phase 'a' current error signal is greater than the triangular wave signal switch S4 (lower device) is ON and switch S1 (upper device) is OFF. If the amplified current error signal corresponding to isaerr is less than the triangular wave, the signal switch S1 is ON and switch S4 is OFF. Similar logic applies to other two phases of VSC of STATCOM.

4.2 Control Algorithm for ELC

To maintain the generated power constant at the generator terminals, the measured power (P_{gen}) is compared with generator rated power (P_r) and power error Per(n) at nth sampling instant is calculated as:

$$P_{er(n)} = P_{r(n)} - P_{gen(n)} \quad (18)$$

where $P_{r(n)}$ is the reference or rated power Pg(n) is the measured power at the nth sampling instant and estimated as:

$$p_{gen} = \frac{1}{\sqrt{3}}\left(v_a i_a + v_b i_b + v_c i_c\right) \quad (19)$$

where v_a ,v_b and v_c are ac voltages and ia, ib and ic are the generator currents. The output of the PI power controller at the nth sampling instant, is expressed as:

$$P^*_{con(n)} = P^*_{con(n-1)} + K_{pp}\{P_{er(n)} - P_{er(n-1)}\} + K_{pi}\, P_{er(n)} \quad (20)$$

where K_{pp} and K_{pi} are the proportional and integral gain constants of the power controller. The PI controller output (P*con(n)) is compared with the triangular carrier (P_{tr}i) waveform and output is fed to the gate of the chopper switch (IGBT)is used in an ELC of DVFC.

$$\begin{aligned} &\text{When } P^*_{con(n)} > P_{tri}, && SD = 1 \text{ and} \\ &\text{When } P^*_{con(n)} < P_{tri}, && SD = 0 \end{aligned} \quad (21)$$

The SD is the switching function used for generating the gating pulse of IGBT of the ELC chopper.

5. MATLAB Based Modelling

The MATLAB model of the DVFC asynchronous generator system consists of the asynchronous machine with capacitor bank and DVFC are realized in MATLAB version 7.3. The modelling of CEAG is carried out using 7.5 kW, 415V, 50Hz, Y-connected cage induction machine and 5kVAR delta-connected excitation capacitor banks. The VF controller is realized with a 3-leg voltage source converter and a diode bridge rectifier based ELC with DC chopper and an auxiliary load. Various loads such as linear, non-linear and dynamic loads are considered here to demonstrate the capability of the VF controller. Simulation is carried out in discrete mode at 10e-6 step size with ode23tb (stiff/ TR-BDF-2) solver.

6. Results and Discussion

The DVFC for IAG system feeding 3-phase 3-wire linear/ non- linear, balanced/unbalanced and dynamic loads are simulated and waveforms of the generator voltage (v_{abc}) and current (i_{abc}), capacitor current (i_{cca}), load current (i_{labc}), STATCOM current (i_{cabc}), ELC current (i_{da}), amplitude of terminal voltage (V_t), DC link voltage (V_{dc}), frequency and speed (f,ω) and variation of power (P_{gen}, Pl_{oad} and P_{dump}) etc are shown in Figs. 3-6. For the simulation, a 7.5 kW, 415V, 14.8A, 4 pole induction machine is used as an asynchronous generator and its parameters are given in Appendix.

6.1 Performance of IAG-DVFC System Feeding Balanced/unbalanced linear Loads

Fig. 3 shows the performance of the DVFC-IAG system with balanced/unbalance resistive loads. At 2.6 sec balanced 3-phase load is applied and the power is drawn by auxiliary load (P_{dump}) which reduces to almost zero. With opening of one phase at 2.75 sec, the load becomes unbalanced and charging and discharging of DC bus capacitor of STATCOM is observed which shows the load balancing aspect of VF controller. It shows that the VF controller maintains the generator power and voltage constant as well as functioning as a load balancer.

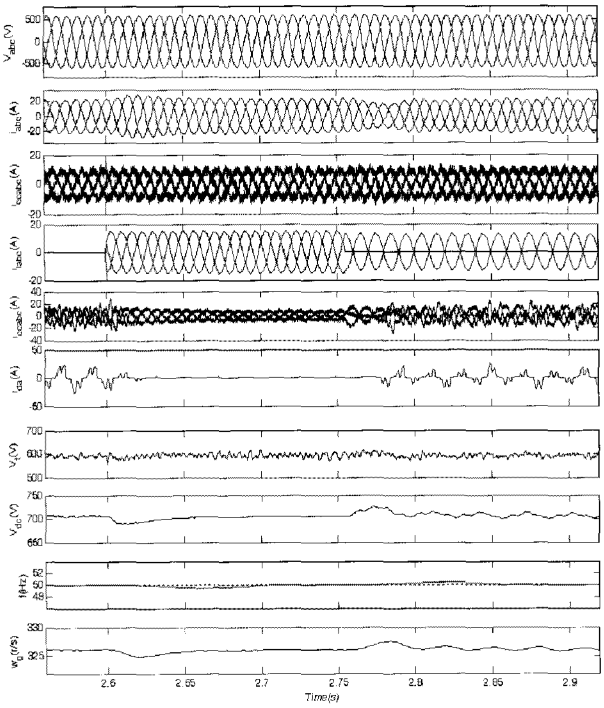

Fig. 3 Transient waveforms of 7.5 kW IAG with DVFC feeding balanced/unbalanced linear resistive load

6.2 Performance of IAG-DVFC System Feeding Balanced/unbalanced Non-linear Loads

Fig. 4 shows the performance of IAG-VFC system feeding balanced/unbalanced non-linear loads using a three phase diode bridge with resistive load and capacitor filter at its DC side. At 2.6 sec a balanced non- linear load is applied and then auxiliary load power (P_{dump}) is reduced for regulating the power, and controller currents (i_{cabc}) become non-linear for eliminating harmonic currents. During load unbalancing at 2.8 sec a ripple in DC bus capacitor (v_{dc}) is observed similarly as with linear loads. Table 1 shows the THD (total harmonic distortion) of generator voltage (v_a) and current (i_a) for no-load and for balanced and unbalanced non-linear load conditions. It can be observed that total harmonic distortion (THD) is less than 5%, the limit imposed by IEEE-519 standard [22].

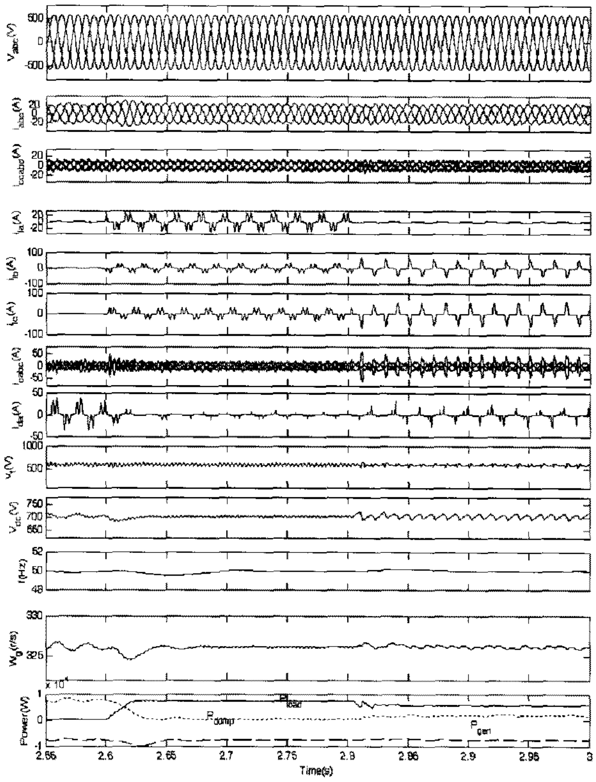

Fig. 4 Transient waveforms of 7.5 kW IAG with DVFC feeding balanced/unbalanced Non-linear load

6.3 Perfomance of IAG-DVFC System Feeding 3-Phase 4-Wire Dynamic Loads

Table 1 Total Harmonic distortion Under Different Non-linear Load Conditions

S.N	Condition of Load	% Total Harmonioc Distortion (THD)			
		v_a	i_a	i_{da}	i_{lc}
1	Balanced Non-linear Load	1.27	2.03	-	66
2	Un-Balanced Non-linear Load	1.29	3.67	67	68

Figs. 5 and 6 show the performance of the proposed IAG system with direct on-line starting of an asynchronous motor and application/removal of a load torque on the running motor respectively. Different transient waveforms of generator voltage (v_{abc}) and generator currents (i_{abc}), excitation capacitor currents (i_{cca}), load currents (i_{labc}), STATCOM currents (i_{cabc}), ELC current (i_{da}), amplitude of terminal voltage (V_t), the DC link voltage (V_{dc}), frequency (f), generator and motor speed (ω_g, ω_m) and motor applied load torque (T_L) power (P_{gen}, P_{load} and P_{dump}) etc are shown in these figures to demonstrate IAG waveforms.

Fig 5 shows the VF controller performance with direct on line starting of a 3-phase asynchronous motor. At 2s it is observed that due to sudden starting of an asynchronous motor, the current flowing through the load controller suddenly reduces to maintain the power at the generator terminal constant.

At 2.4 s the load torque is applied on the motor as shown in Fig 6, then the current in the stator winding of the motor is increased and the current drawn by the auxiliary load is reduced due to action of the VF controller while voltage and current at the generator terminal remain constant. At 2.75 s when the load torque on the motor is removed the current drawn by the motor is reduced and additional generated power is absorbed by the auxiliary load. In this way the controller functions as voltage and frequency controller.

7. Conclusion

The performance of the proposed voltage and frequency controller has been demonstrated for an isolated power generation system and for feeding various types of consumer loads such as linear/non-linear, balanced/unbalanced and dynamic loads. Here it is observed that the controller responds in a desired manner and regulates the system voltage and frequency under direct on line starting of the asynchronous motor and application/removal of load torque. In addition, the proposed VF controller also functions as a harmonic eliminator, load balancer for feeding linear/non-linear balanced/unbalanced loads.

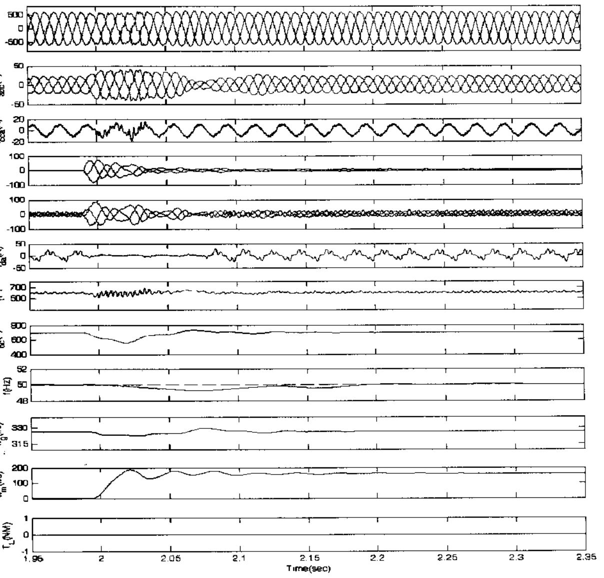

Fig. 5 Transient waveforms during direct online starting of an asynchronous motor load in proposed electrical system

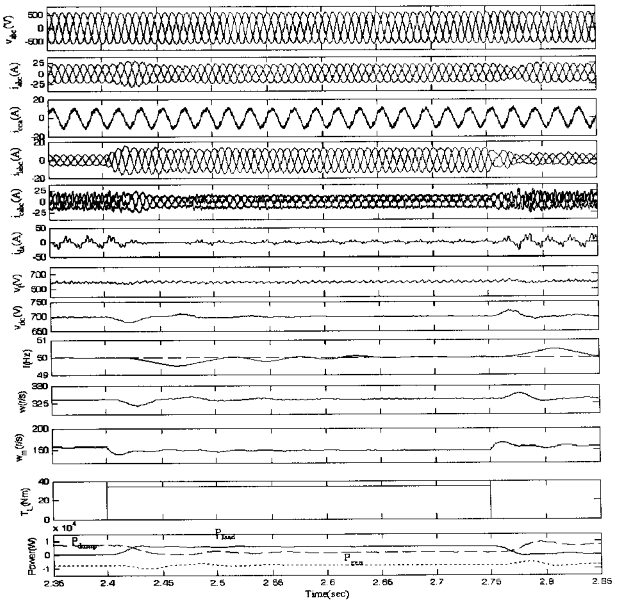

Fig. 6 Transient waveforms during the load torque application and removal of motor load

Appendix

8.1 The Parameters of 7.5kW, 415V, 50Hz, Y-Connected, 4-pole Asynchronous Machine used as AG are given below

$R_s = 1\Omega$, $R_r = 0.77\Omega$, $X_{lr} = X_{ls} = 1.5\Omega$, $J = 0.1384$ kg-m^2
$L_m = 0.134$ $(I_m<3.16)$
$L_m = 9e{-}5I_m^2 - 0.0087I_m + 0.1643$ $(3.16<I_m<12.72)$
$L_m = 0.068$ $(I_m>12.72)$

8.2 The Parameter of 4kW, 415V, 50Hz, Asynchronous Machine as a Motor Load

$R_s = 1.4\Omega$, $R_r = 1.39\Omega$, $X_{lr} = X_{ls} = 1.8\Omega$, $J = 0.0131$ kg-m^2.

8.3 Non- Linear Load

Three phase diode bridge with capacitor filter of 1000μf and resistive load of 7kW.

8.4 Controller Parameters

$L_f = 5$mH, $R_f = 0.1\Omega$, and $C_{dc} = 4000\mu$F, $R_{d2} = 35\Omega$ $K_{pa} = 0.03$, $K_{ia} = 0.001$, $K_{pd} = 0.12$, $K_{id} = 0.014$ $K_{pp} = 0.07$, $K_{pi} = 0.02$

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