LOAD LOSS PERFORMANCE OF AN AUTONOMOUS SELF-EXCITED INDUCTION GENERATOR

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Abstract

This paper presents a dynamic analysis of an autonomous Self-Excited Induction Generator (SEIG) showing dynamic loss of load performance. In stand-alone operation of the SEIG, especially when supplying a low power utility, an interesting performance of the SEIG observed for various power factor loads can be harnessed to maximise the use of the SEIG. Analysis is carried out based of the d-q axis model, while considering the performance characteristics of the machine at constant machine speed, capacitor value and for various power factor loads. The transient surge, its decay and rise on the various machine variables phase voltage, phase current, capacitor current and load current are investigated for a gain and subsequent loss of load. The time it takes to excite the machine is also considered for the various power factors on an unloaded condition. The effects of the loading on the frequency, as well as the drop in the value of the monitored parameters are also investigated.

Keywords: ?, ?, ?, ?, ?,

1. Introduction

The high demand for renewable and a more environmental friendly source of energy has led to investigation of other energy sources like wind, solar, biomass, etc. The Induction generator (IG) has been found to be suitable for wind energy conversion and also in small hydro plants [1, 2]. This has also increased the level of research in Induction Generators (IGs) which was thought to have very less or no practical applications [3]. Researchers have found that a Self-Excited Induction Generator (SEIG) could be used with a conventional energy sources to generate power. An Induction machine (IM) has the ability to operate as a motor or a generator depending on the required mode of operation.

As a generator it has numerous advantages over the conventional synchronous generators especially when operating under stand alone mode [4]. A Self Excited Induction Generator (SEIG) has a peculiar characteristic, since there is a great necessity to sustain excitation even when the machine is loaded. SEIG also has a problem of voltage and frequency regulation, especially when using a variable speed prime-mover (example in wind power generation). To maintain a constant voltage and frequency, different control models and methods were given by different authors. The control methods include a mechanical control involving stall control, pitch control and yaw control [5]. The other types of control involve the use of a load controller and a VAR compensator

[5, 6, 7, 8, 9, 10].

The SEIG has an advantage of being rugged, very reliable, easily available etc. It has numerous advantages over the synchronous generator when used with a variable prime mover, and also find its applications in the area of electric breaking [7, 11], but delivering power to ordinary growing load for a long time might need the parallel combination of generators.

The paper by Wang and Su [12] presented the dynamic performance of SEIG under various loading conditions, while considering the behaviour of the terminal voltage for a unity, leading and lagging power factor conditions, and also the machine behaviour when the excitation capacitor is disconnected.

Despite the advantages and usability of SEIG, it still has the problem of voltage and frequency stabilization, thus always requiring a good voltage and frequency stabilization scheme. SEIG, therefore, is speed, excitation source and load dependent. For a constant speed, non- variable capacitance operation, it is observed that the frequency varies owing to the introduction or removal of load. Since SEIG derives its excitation from a reactive source, the introduction of a reactive load changes the operating state of the generator.

This paper investigate the dynamic loss of load performance of an autonomous SEIG for various power factor values, considering the surge experienced by the machine characteristics of phase current, load current, capacitor current, phase voltage and the change in frequency during a load introduction and subsequent removal of the introduce load on the machine.

A relationship between the power factor value and the time taken for the surge experienced during loading and unloading to rise or settle is also investigated, while considering the effect of the load on frequency for the various power factors.

2. Modelling of SEIG

For the modelling of SEIG, the iron and the rotational losses are neglected, while the magnetizing inductance is used instead of the magnetizing reactance since it varies with the frequency.

Using an induction motor with the specification 3.6KW, 415V, 7.8A, 4 poles, 50HZ, stator resistance (R_s) of 1.66Ω, stator Inductance (L_s) of 11.4mH, rotor resistance (R_r) of 2.74Ω and rotor inductance (L_r) of 11.4mH, the relationship between the magnetizing inductance and the phase voltage obtained by finite element method is given in (1).

$$\begin{aligned} L_m &= -1.56 \times 10^{11} V_{ph}^4 + 2.44 \times 10^{-8} V_{ph}^3 \\ &\quad -1.19 \times 10^{-5} V_{ph}^2 + 1.42 \times 10^{-3} V_{ph} + 0.245 \end{aligned} \tag{1}$$

This relationship between L_m and V_{ph} as given by [11] takes into account the effect of the magnetizing inductance on self-excitation. To accommodate both the transient and the steady state analysis, the system is modelled dynamically using the $d-q$ axis model in the stationary reference frame, thus giving a complete solution. The $d-q$ model of a loaded SEIG for a shorted rotor is given in Figure 1.

A load represented by Z_L is connected across the excitation capacitor to represent the loaded condition of the SEIG.

For an unloaded condition, Z_L is disconnected to give an open circuit and can be described with equation 2. Where, $D = L_m L_r - L_m^2$, ω_r is the electric rotor angular speed in rads/s, V_{qs} and V_{ds} are the q and d-axis stator voltages respectively, V_{qr} and V_{dr} are the q and d-axis rotor voltages respectively, i_{qs} and i_{ds} are q and d-axis stator current respectively while i_{qr} and i_{dr} are the q and d-axis rotor currents respectively.

The analysis of the loaded and unloaded condition is similar, because the load Z_L is the only component modifying the unloaded circuit. This component also introduce the load current (i_{dL} and i_{qL}) and the capacitor current

$$\begin{bmatrix} pi_{qs} \\ pi_{ds} \\ pi_{qr} \\ pi_{dr} \\ pV_{qs} \\ pV_{ds} \end{bmatrix} = \frac{1}{D}\left(\begin{bmatrix} -L_rR_s & \omega_rL_m^2 & L_mR_r & -\omega_rL_rL_m & -L_r & 0 \\ \omega_rL_m^2 & -L_rR_s & \omega_rL_rL_m & L_mR_r & 0 & -L_r \\ R_sL_m & \omega_rL_mL_s & -L_sR_r & \omega_rL_rL_s & L_m & 0 \\ -\omega_rL_mL_s & R_sL_m & -\omega_rL_rL_s & -L_sR_r & 0 & L_m \\ \frac{D}{C} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{D}{C} & 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \\ V_{qs} \\ V_{ds} \end{bmatrix}\right) \tag{2}$$

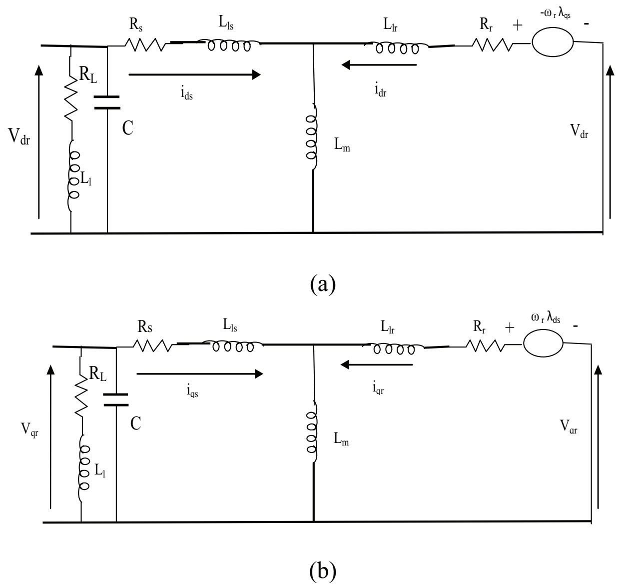

Figure 1: $d-q$ model of a loaded SEIG in a stationary reference frame (a) d-axis circuit (b) q-axis circuit.

(i_{dC} and i_{qC}) in the circuit. For an unloaded machine, the capacitor current equals the stator winding current. The terminal voltages which also correspond to the voltages across the shunt capacitors are:

$$pV_{qs} = \frac{i_{qs} - i_{qL}}{C} - \omega_r V_{ds} \tag{3}$$

$$pV_{ds} = \frac{i_{ds} - i_{dL}}{C} - \omega_r V_{qs} \tag{4}$$

The load equations, also transformed to $d-q$ frame are given by:

$$pi_{qL} = \frac{V_{qs} - R_L i_{qL} - \omega_r L_L i_{dL}}{L_L} \tag{5}$$

$$pi_{dL} = \frac{V_{ds} - R_L i_{dL} - \omega_r L_L i_{qL}}{L_L} \tag{6}$$

Thus, the dynamic equation for the SEIG for a shorted rotor can thus be given in equation (7).

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_spL_s & 0 & pL_m & 0 \\ 0 & R_spL_s & 0 & pL_m \\ pL_m & -\omega_rL_m & R_rpL_r & -\omega_rL_r \\ \omega_rL_m & pL_m & \omega_rL_r & R_r + pL_r \end{bmatrix}\begin{bmatrix} -i_{qs} \\ -i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{7}$$

Equations (3) to (7) give the machine equations, the voltage equations and the load equations for the SEIG supplying an $R-L$ load.

3. Excitation of SEIG

For an Isolated IG to generate voltage, and to supply power irrespective of the stator speed, an excitation has to be provided. For SEIG to be self-excited, there must exist sufficient residual magnetism in the rotor and the three phase AC capacitor bank should be of sufficient value.

If a charged capacitor is connected to the stator terminal of an induction generator, these can supply the needed reactive power. This excitation current from the charged capacitor will flow to produce a magnetic flux or assist the residual magnetic flux. This magnetic flux will then induce voltage which will be able to build up charge in the capacitors. The process is continued, thus producing a higher generated voltage until saturation is reached. However, if there is residual magnetic flux in the rotor magnetic field, this flux induces voltage to charge the capacitor. The build up process is then repeated for the magnetic flux and the capacitor voltage until saturation is reached [11].

At saturation, the flux becomes constant, thus bringing about a steady state condition for the voltage. The rise of current and voltage are influenced by the magnetic saturation in the induction machine. However, there is a

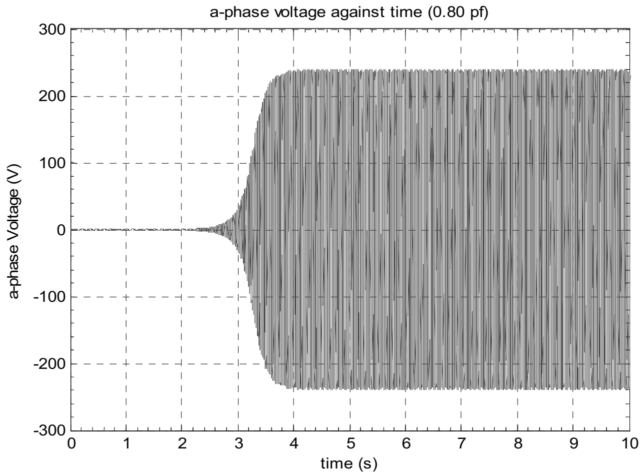

Figure 2: Phase voltage build up.

Table 1: Relationship between power factor and voltage build up.

Power Factor	0.80	0.86	0.88	0.90	0.96	0.99
Build up time (sec)	4.3	4.4	4.53	4.6	4.63	4.65

minimum speed for a corresponding capacitor value for self-excitation to occur [11].

Various ways of exciting induction generators is possible since the process of excitation is to provide sufficient reactive power for the generator.

4. Simulation of the Dynamic Process

MATLAB/SIMULINK package is used to simulate the machine characteristics of phase voltage, phase current, load current, capacitor current during self-excitation and voltage build up process before loading. The machine is driven at a given speed and appropriate capacitor value connected to the stator terminals of the machine.

The self-excitation process is observed for 0.8, 0.86, 0.88, 0.90, 0.96 and 0.99 power factor loads on a start up load of 200 ohms. Equation (2) which encompasses the machine and the capacitor equation is used for the simulation. The result of the simulation for the phase voltage are shown in Figures 2 and 3 and Table 1.

It is observed that the build up time for the generator increases with increasing power factor load.

5. Dynamic Loss of Load Performance

The dynamic equation for the loaded circuit as given in (3) to (7) and (1) for the magnetizing inductance characteristics is used for the simulation with the test parameters. The machine is started with 200 ohm load and then loaded with 100 ohms load after ten seconds, the 100 ohms load is subsequently removed after 15 seconds of operation. The machine characteristics of phase voltage, phase current, capacitor current and load current are investigated. The loss of load performance is also explicitly presented, monitoring the surge magnitude and the time it takes for it to completely die down. This conditions is investigated for 0.80, 0.86, 0.88, 0.90, 0.96, 0.99 power factor loads. This machine is operated at a constant speed, constant capacitor value and a non-variable load.

The value of the phase voltage is observed to increase with an increasing power factor value. During loading, the difference in the drop on the voltage value decreases as the power factor increases. The difference in the value of both the surge at loading and the surge developed when the machine is unloaded increases as the power factor increases. The time taken for the surge experienced during loading varies about 1.6 seconds but there is a significant drop to a value of 1.2 seconds for the 0.99 power factor load. These characteristics are shown in Figure 4 and Table 2.

The value of the phase current increases as the power factor increases, while the difference in the value of the current drop experienced at loading and subsequent unloading decreases with increasing power factor. The time for the surge at loading to die down does

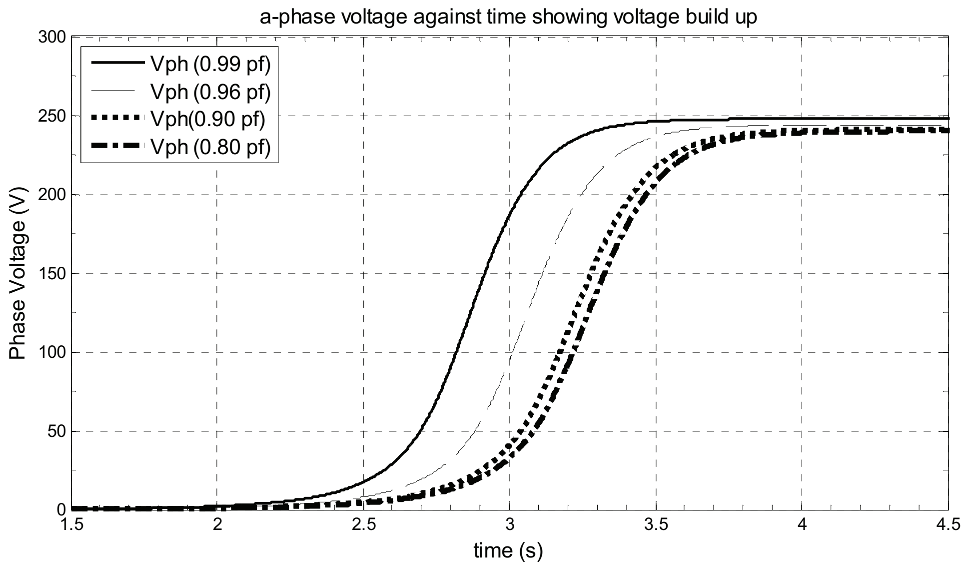

Figure 3: Phase voltage build up for various power factor loads.

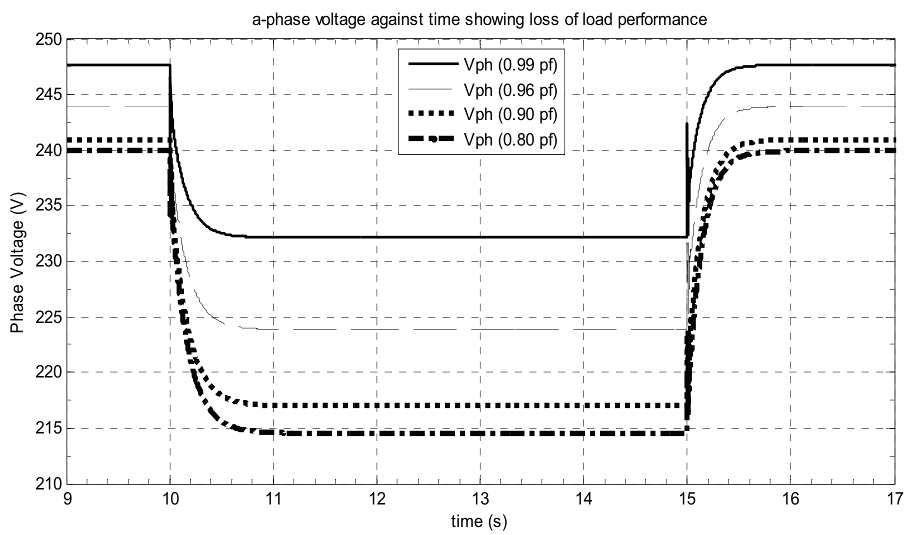

Figure 4: Phase Voltage showing loss of load performance.

Table 2: Loss of load performance for Phase voltage.

	Power factor		0.80	0.86	0.88	0.90	0.96	0.99
Time	T_1(Surge fall time) (sec)		1.6	1.55	1.57	1.5	1.3	1.25
	T_2 (Surge rise time) (sec)		1.4	1.2	1.3	1.3	1.4	1.1
Phase voltage (V)	V_1 (V) Surge Magnitude	Max value	238.8	240.1	240.5	240.7	243.8	247.5
		Min value	235.2	234.7	234.8	234.2	235.8	237.5
		Difference	3.6	5.4	5.7	6.5	8	10
	V_2 (V) Surge Magnitude	Max value	219.6	220	221.8	223.6	231.8	242.5
		Min value	216.5	215	215.5	216.8	223.5	232.8
		Difference	3.1	5.0	6.3	6.8	8.3	9.7
	Value b/4 loading (V)		239.85	240.07	240.38	240.8	243.8	247.5
	Value at loading (V)		214.4	214.94	215.7	216.8	223.5	232.1
	Drop in value		25.45	25.13	24.68	24	20.3	15.4

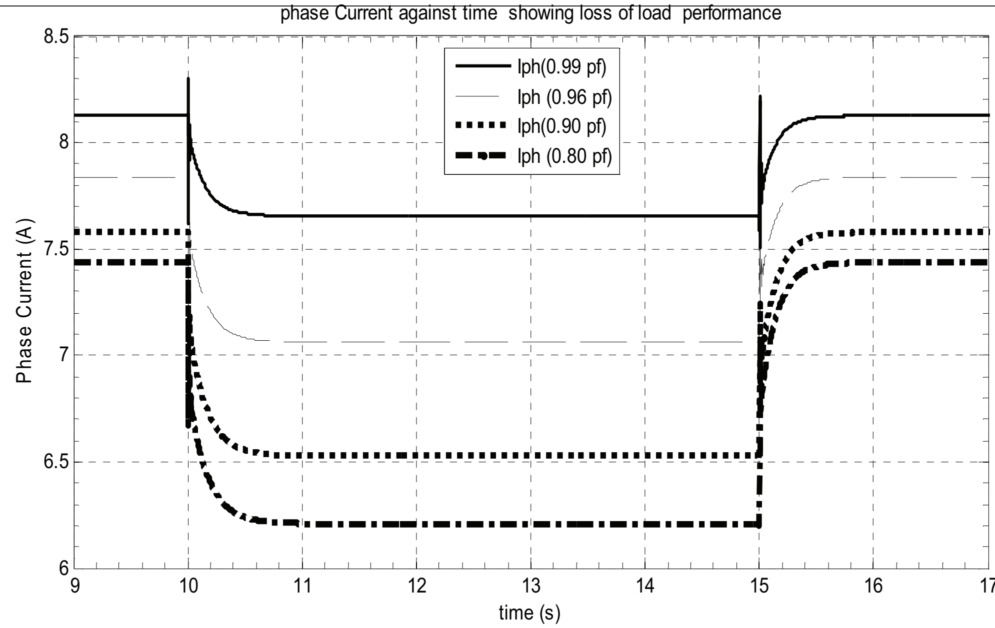

Figure 5: Phase Current showing loss of load performance.

not show a sharp difference across the power factor loads, but a significant decrease is observed for the 0.99 power factor load. The same non significant change is observed in the case of the time taken for the unloading surge to die down. This behaviour is illustrated in Figure 5 and Table 3.

The value of the capacitor current increases with increasing power factor, but the difference in the drop of the capacitor value decreases with increasing power factor load. The difference in the magnitude of the surge of both the loading condition and unloading condition increases with increasing power factor load. No significant difference is observed in the time taken for the surge developed during the loading condition and the unloading condition to die down, but only shows a sharp decrease for the 0.99 power factor load. These characteristics are shown in Figure 6 and Table 4.

The value of the load current increases with increasing power factor load, but the difference in the drop of the load current during loading and subsequent unloading increases as the power factor increases. No sharp difference is observed in the settling time for the surges, but there is a noticeable drop for the 0.99 power factor value. The same non obvious difference is observed in the difference of the magnitude of the surges across the power factor loads.

These relationships are shown in Figure 7 and Table 5.

In Table 6, the frequency of the machine is dropped by a value of 0.26 Hz for the power factor loads of 0.80, 0.86, 0.88 and 0.25Hz for the power factor loads of 0.90, 0.96 and 0.99. The frequency is observed to be dependent on speed, the capacitor value and the load value after starting. This observed drop in frequency amounts to a value of about 0.5%.

6. Conclusion

The value of the phase voltage, phase current, capacitor current and load current, all increases with increase in power factor load, but only the load current has its value of current drop at loading decreasing with increasing power factor as compared to the other monitored characteristic which increases with increasing power factor load. The build up time for the parameters considered (phase voltage, phase current, capacitor current and load current) all increases with increasing

Table 3: Loss of load performance for phase current.

	Power factor		0.80	0.86	0.88	0.90	0.96	0.99
Time	T_1(Surge fall time) (sec)		1.44	1.7	1.7	1.7	1.7	1.4
	T_2 (Surge rise time) (sec)		1.4	1.2	1.3	1.3	1.4	1.2
Phase current	I_1 (A) Surge Magnitude	Max value	6.9	7.02	7.18	7.25	7.85	8.32
		Min value	6.7	6.72	6.8	6.9	7.25	7.56
		Difference	0.2	0.3	0.38	0.35	0.75	0.82
	I_2 (A) Surge Magnitude	Max value	6.92	7.09	7.12	7.22	7.68	8.27
		Min value	6.19	6.31	6.4	6.85	7.04	7.51
		Difference	0.73	0.78	0.72	0.58	0.7	0.82
	Value b/4 loading (V)		7.43	7.49	7.53	7.57	7.83	8.27
	Value at loading (V)		6.20	6.34	6.42	6.52	7.05	7.51
	Drop in value		1.22	1.15	1.11	1.05	0.78	0.78

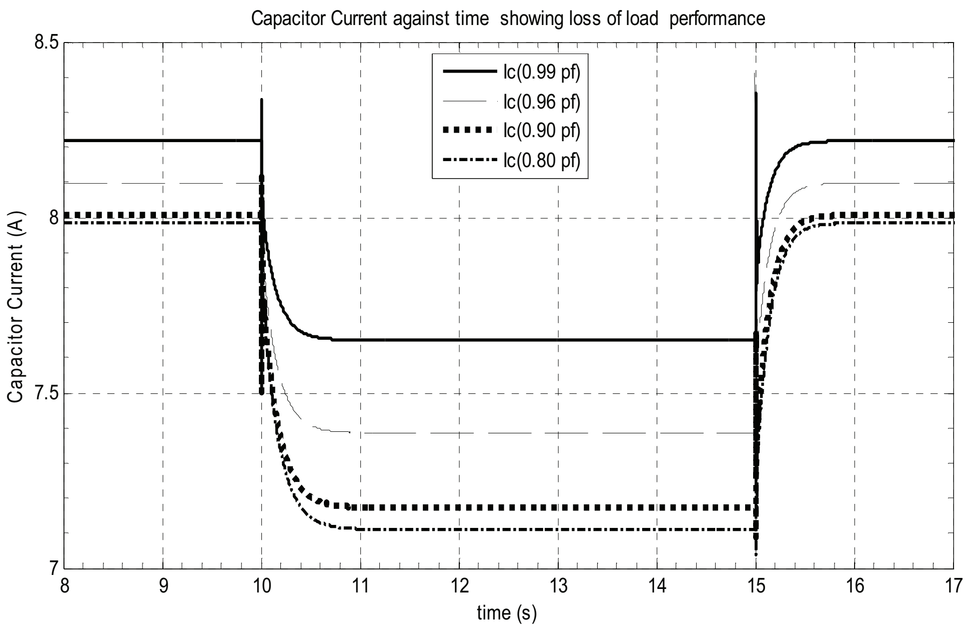

Figure 6: Capacitor Current showing loss of load performance.

Table 4: Loss of load performance for capacitor current.

	Power factor		0.80	0.86	0.88	0.90	0.96	0.99
Time	T_1(Surge fall time) (sec)		1.5	1.55	1.6	1.7	1.7	1.2
	T_2 (Surge rise time) (sec)		1.3	1.35	1.4	1.4	1.3	1.0
Phase current	P_1 (A) Surge Magnitude	Max value	8.08	8.09	8.1	8.12	8.23	8.34
		Min value	7.62	7.59	7.52	7.52	7.48	7.52
		Difference	0.64	0.5	0.58	0.6	0.75	0.82
	P_2 (A) Surge Magnitude	Max value	7.44	7.55	7.6	7.66	7.98	8.38
		Min value	7.03	7.03	7.04	7.08	7.28	7.6
		Difference	0.41	0.52	0.56	0.53	0.7	0.78
	Value b/4 loading (V)		7.983	7.98	7.99	8.00	8.1	8.23
	Value at loading (V)		7.1085	7.11	7.13	7.17	7.38	7.65
	Drop in value		0.8745	0.86	0.85	0.83	0.72	0.58

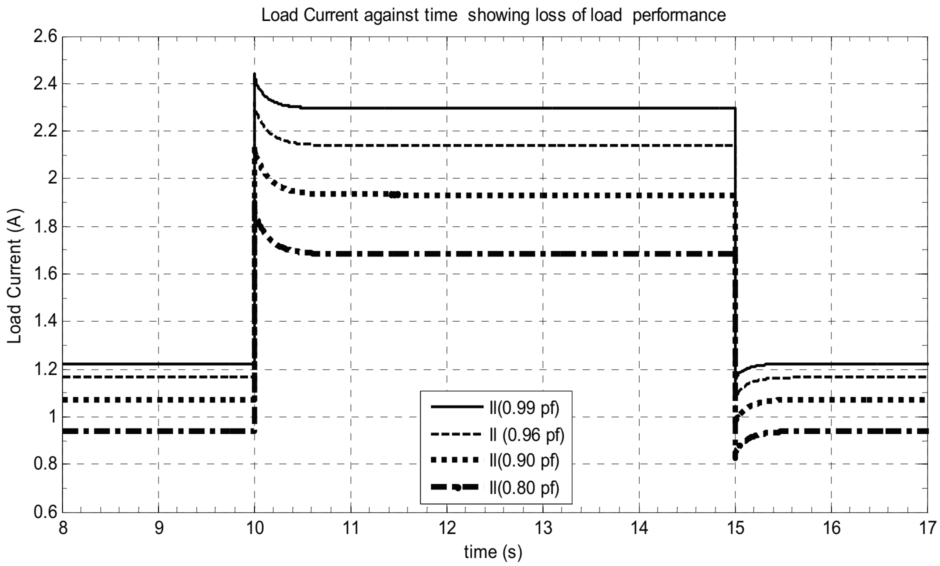

Figure 7: Load Current showing loss of load performance.

Table 5: Loss of load performance for Load current.

	Power factor		0.80	0.86	0.88	0.90	0.96	0.99
Time	T_1(Surge fall time) (sec)		1.8	1.7	1.6	1.6	1.7	1.5
	T_2 (Surge rise time) (sec)		1.6	1.3	1.4	1.4	1.4	1.0
Load current	I_1 (A) Surge Magnitude	Max value	1.90	2.035	2.081	2.135	2.313	2.435
		Min value	1.84	2.005	2.053	2.105	2.273	2.364
		Difference	0.006	0.003	0.028	0.03	0.04	0.071
	I_2 (A) Surge Magnitude	Max value	0.86	0.926	0.9551	0.985	1.13	1.19
		Min value	0.823	0.908	0.935	0.966	1.077	1.157
		Difference	0.037	0.018	0.0201	0.019	0.053	0.033
	Value b/4 loading (V)		0.939	1.016	1.043	1.072	1.165	1.23
	Value at loading (V)		1.682	1.823	1.876	1.933	2.14	2.3
	Drop in value		0.742	0.807	0.833	0.861	0.975	1.07

Table 6: Loss of load performance for Load current.

	Power factor	0.80	0.86	0.88	0.90	0.96	0.99
Frequency (Hz)	Frequency at starting	50.76	50.76	50.76	50	50	50
	Frequency at loading	50.5	50.5	50.5	49.75	49.75	49.75

power factor load.

The phase voltage, the phase current and the capacitor current has the difference in the magnitude of the surge experienced during loading and subsequently unloading of the machine increasing with increasing power factor load, while the load current does not show any significant increase with the power factor. The settling time of the monitored characteristic does not show a significant variation with the power factor value except for the phase voltage during loading. The frequency also varies with the load, capacitor value and more significantly with the machine speed. The variation of this frequency about the machine frequency at loading is about 0.5% for the considered power factor values.

An averagely near unity power factor load should be considered for the machine since a not so high value for the difference in surge value and average increase in the state variables considered will be recorded. The settling time also deviates about 1/10 of a second about the mean value. Since the voltage and the frequency varies with the load, capacitor value and the machine speed, a good regulation and stabilization system is still necessary for a good machine operation.

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