EFFECTS ON MAJOR POWER QUALITY ISSUES DUE TO INCOMING INDUCTION GENERATORS IN POWER SYSTEM

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ABSTRACT

This paper presents a laboratory study on 'effects of integration of induction generators on grid power quality parameters such as voltage, frequency power factor, harmonics and reactive power'. Study is carried out with different switching sequence of grid connected induction generators. The analysis is done with two squirrel cage induction generators and one wound rotor induction generator coupled to DC shunt motors. Experimental results as obtained with different switching sequence are found to be very interesting and useful for final recommendations.

Keywords: induction generator, power quality, harmonics, flicker, reactive power, voltage, frequency.

1. INTRODUCTION

With rapidly growing electricity demand and increased uncertainty over fossil fuel resources, the worldwide integration of wind generation into power networks is growing apace. In particular, it is already judged technically feasible for European power systems to achieve a penetration of 20% of power from wind, with significant contributions from off-shore wind farms. Wind energy conversion systems often produce power and voltage varying with natural conditions (wind speed) [1]. Grid connection of these sources is essential if they are ever to realize their potential to significantly alleviate the present day problems of atmospheric pollution and global warming. However, electric utility grid systems cannot readily accept connection of new generation plant without strict conditions placed on voltage regulation due to real power fluctuation and reactive power generation or absorption, and on voltage waveform distortion resulting from harmonic currents.

According to available references on power quality of induction generators or wind generators, current harmonics and transient currents during grid connection of two 225 kW wind induction generator with pitch control were examined by T. Thiringer [2]. The prediction of synchronous and asynchronous harmonics generated by induction generators using time domain measurement was proposed by M. G. Ioannides [3]. S. S. Yegna Narayanan *et al.*, Investigated transient and harmonics of a grid connected induction generator (GCIG) driven by a wave-energy turbine [4]. Harmonic components in over voltage waveform and post-fault conditions of both induction generator and synchronous generator were studied and discussed by W. E. Feero [5]. Ferro resonance of dispersed system generation (DSG) using induction generator connected to a small distribution system under islanding operation was presented by W. B. Gish [6]. Power, efficiency, and current unbalance of a wind induction generator (WIG) connected to an unbalanced grid using symmetric components were examined [7]. Other power-quality analyses on wind generators by researchers can be referred to [8-21].

In this paper an attempt is made to investigate the effect of switching sequence and instants of incoming induction generators on the grid performance. For this purpose an experimental setup comprising of three independent induction generators is considered and its details are discussed in the next section. Experimental observations as obtained are used to frame the final recommendations.

2. SYSTEM CONFIGURATION

Figure-1 shows the three phase schematic diagram of the studied system. It comprises of three induction machines coupled with dc motors which are capable to provide the input to generator at any speed thus represents a wind turbine. All induction machines are operated as grid connected induction generators (GCIGs) with a common resistive load across stator terminals.

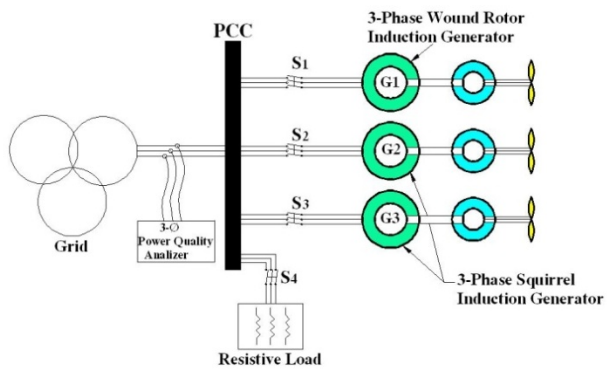

Figure-1. Schematic diagram.

Under such operations the reactive power required for induction generators will be drawn from the grid and the operation is possible only for machine speed higher than the synchronous speed. The measurements are made with three phase power quality analyzer (Fluke model 435) at the point of common coupling (PCC) as shown. Specifications of system components are as:

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Generator 1 [G1]
3-Phase, 4- pole, 415V, 50 Hz, 3.5 kW wound rotor induction machine.

Generator 2 [G2]
3-Phase, 4- pole, 50 Hz, 415 V, and 2.2 kW star connected, squirrel cage induction machine.

Generator 3 [G3]
3-Phase 4- pole, 50 Hz, 415 V, 2.2 kW star connected, squirrel cage induction machine.

Load
A 3-phase variable resistive load of 20 kW. Always remain intact with PCC irrespective of generator operation.

Power quality analyzer
Maximum voltage : 1000Vrms (6kV peak)
Maximum Sampling speed : 200kS/s on each channel simultaneously
THD Measurement range : 0.0 to 100%
Accuracy : ±2.5%V and A
VAR measurement range : 1.0 to 20.00MVA
Accuracy : ±1%
Power factor accuracy : ±0.03

3. SYSTEM OPERATION AND MEASUREMENT

In order to investigate the switching effects of incoming induction generators, all the machines are run at speeds which are higher than the corresponding synchronous speed. At this movement all the three switches as shown in Figure-1 i.e. S_1, S_2 and S_3 must be open. As soon as, any one of the switch is closed, the corresponding machine start working as an induction generator. Further depending upon the switching sequences of generators following cases may be taken up for investigating the switching effects.

Case-I [Switching Sequence; $S_1 \rightarrow S_2 \rightarrow S_3$]
Case-II [Switching Sequence; $S_1 \rightarrow S_2$ and S_3 simultaneously]
Case-III [Switching Sequence; $S_2 \rightarrow$ S1 and S_3 simultaneously]
Case-IV [Switching Sequence; $S_3 \rightarrow$ S1 and S_2 simultaneously]
Case-V [Switching Sequence; S_1, S_2 and S_3 all simultaneously]

a) Case -I [Switching Sequence 1-2-3]

Table-1 shows the speed of grid connected induction generators (GCIGs) after switching into the grid.

Table-1. Speed of generators.

Particulars	**Speed** (rpm)
GCIG no1	1550
GCIG no 2	1530
GCIG no 3	1540

Table-2 shows the switching operation of three GCIGs. Under this case study, first of all G_1 is switched in and then G_2 after small interval. Finally G_3 is switched on at instant 4:57. Figure-2 to Figure-6 shows the experimental observations for total current harmonics distortion (THD A) in three lines, total voltage harmonic distortion (THD V), reactive power drawn from grid, power factor at PCC and line currents at PCC.

Table-2. Switching instants in case-I.

Particulars	**Switching instant**
No GCIG in circuit	01:47
GCIG 1	01:57
GICG 2	03:27
GCIG 3	04:57

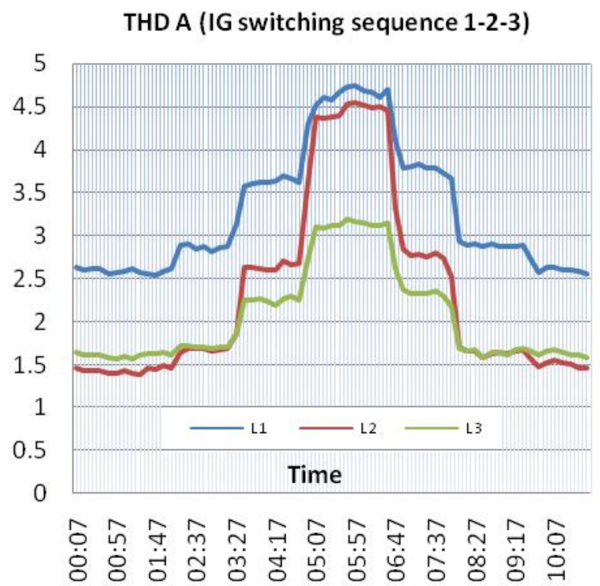

Figure-2. Total harmonic distortion in currents on three phases.

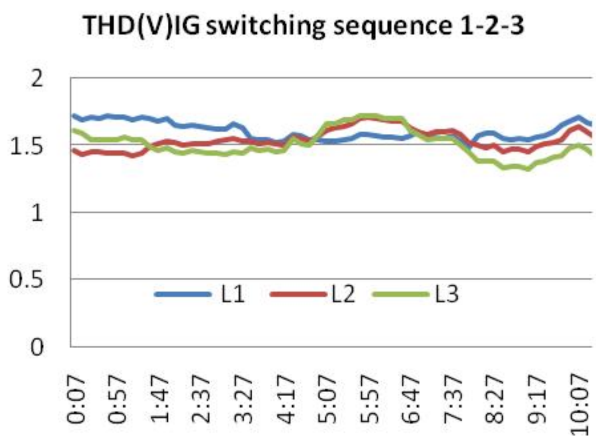

Figure-3. Total harmonic distortion in voltages on three phases.

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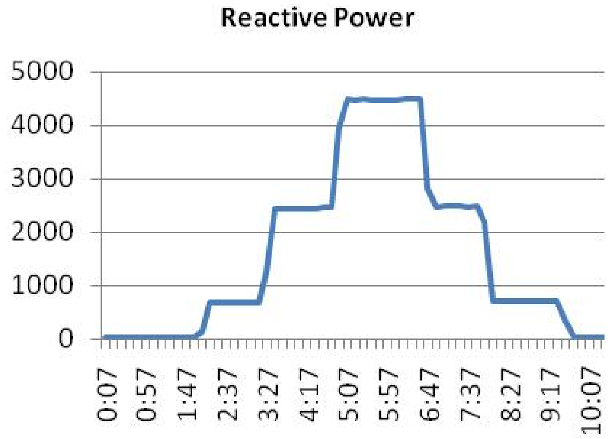

Figure-4. Variation in reactive power with switching of GCIGs.

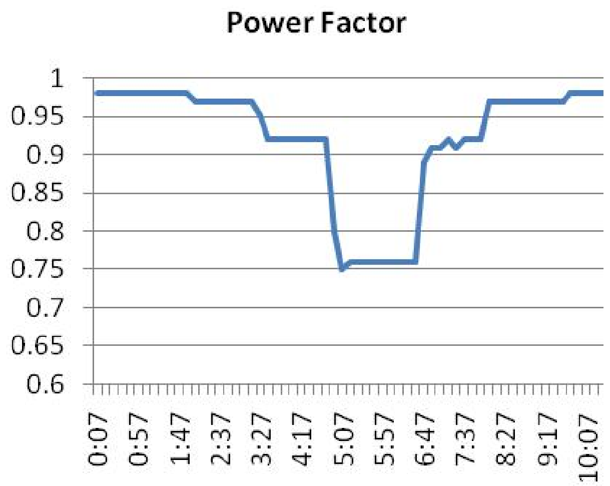

Figure-5. Variation in power factor with switching in of three GCIGs.

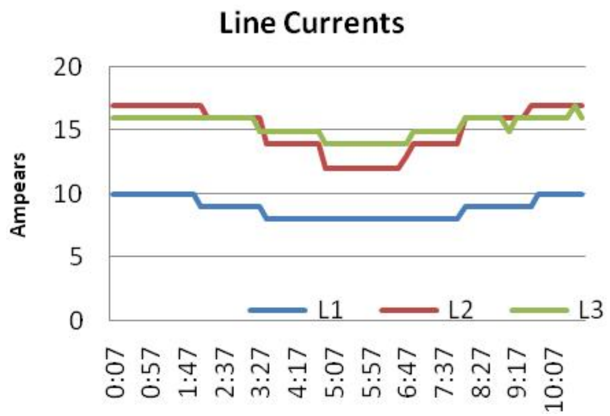

Figure-6. Variation in line currents.

b) Case-II [Switching Sequence; S1→ S2 and S3 simultaneously]

Table-3 gives the switching instants of three induction generators under this case study.

Table-3. Switching instants in case -1I.

Particulars	Switching instant
No GCIG in grid	Before 1:24s
GCIG 1 switched in	1:24s
GCIG 2 and 3 switched in	3:04s
GCIG 2 and 3 switched off	4:44s
GCIG 1 switched off	5:44s

Figure-7 to Figure-11 shows the experimental observations for total current harmonics distortion (THD A) in three lines, total voltage harmonic distortion (THD V), reactive power drawn from grid, power factor at PCC and line currents at PCC.

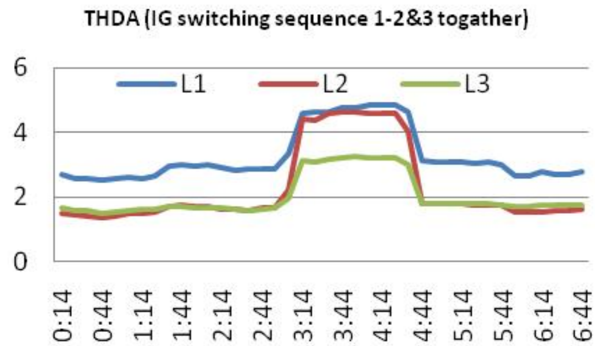

Figure-7. Total harmonic distortion in currents on three phases.

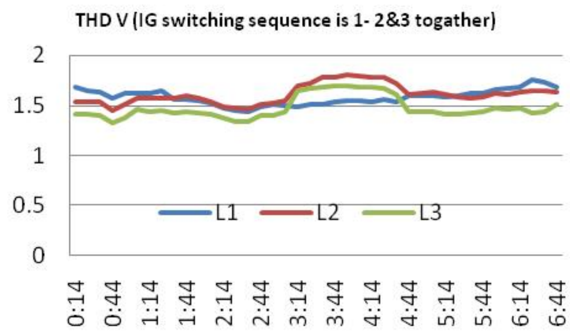

Figure-8. Total harmonic distortion in voltages on three phases.

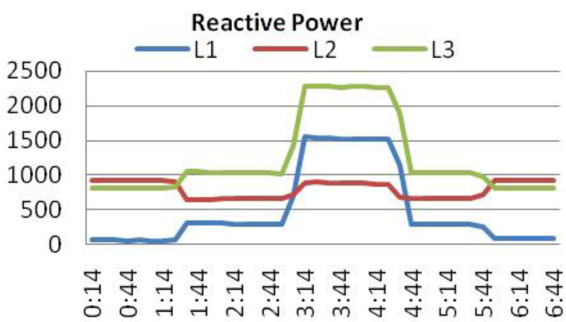

Figure-9. Variation in reactive power with switching of GCIGs.

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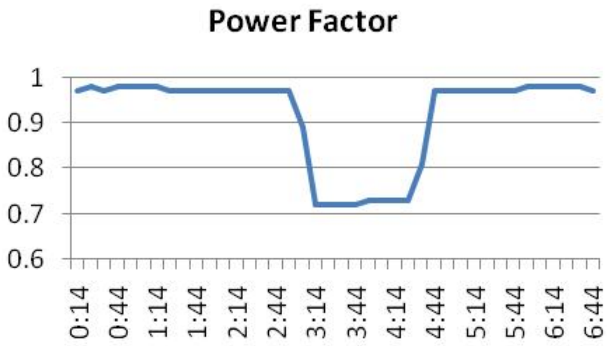

Figure-10. Variation in power factor with switching in of three GCIGs.

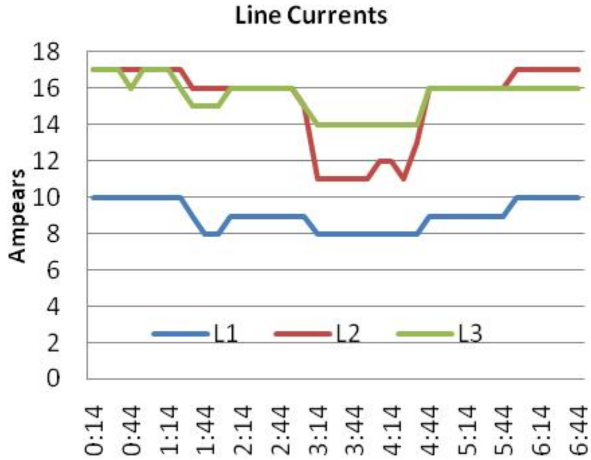

Figure-11. Variation in line currents.

c) **Case-III** [Switching Sequence; S2 → S1 and S3 simultaneously]

Table-4 gives the switching instants of three induction generators under this case study.

Table-4. Switching instants in case -III.

Particulars	Switching instant
No GCIG in grid	Before 2:03s
GCIG 2 switched in	2:03s
GCIG 1and 3 switched in	4:53s
GCIG 1and 3 switched off	6:13s
GCIG 2 switched off	7:43s

Figure-12 to Figure-16 shows the experimental observations for total current harmonics distortion (THD A) in three lines, total voltage harmonic distortion (THD V), reactive power drawn from grid, power factor at PCC and line currents at PCC.

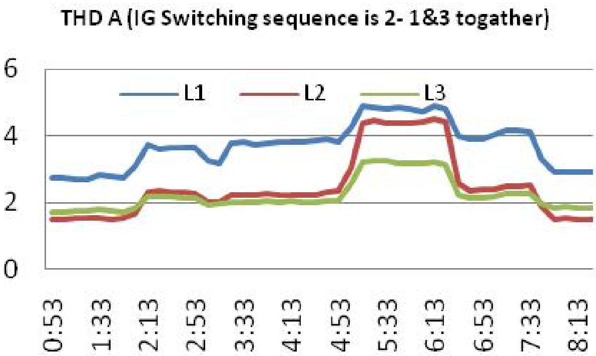

Figure-12. Total harmonic distortion in currents on three phases.

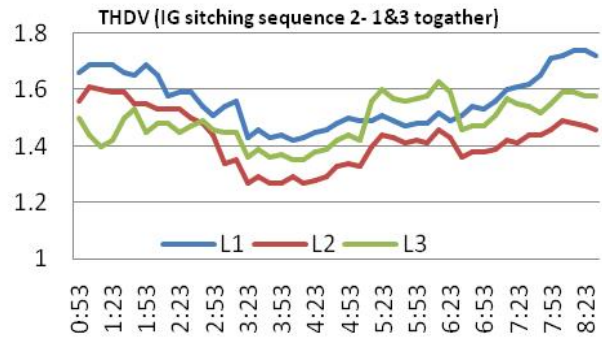

Figure-13. Total harmonic distortion in voltages on three phases.

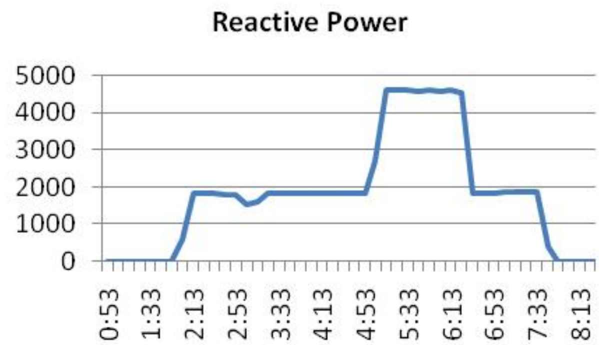

Figure-14. Variation in reactive power with switching of GCIGs.

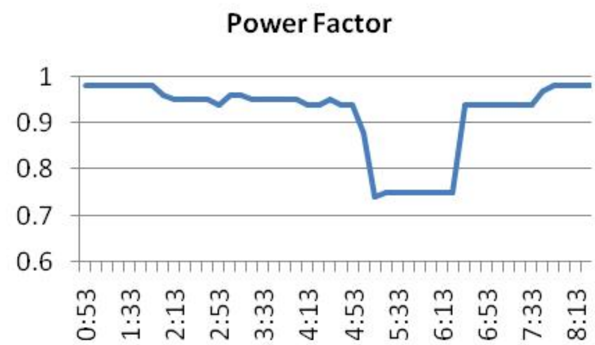

Figure-15. Variation in power factor with switching in of three GCIGs.

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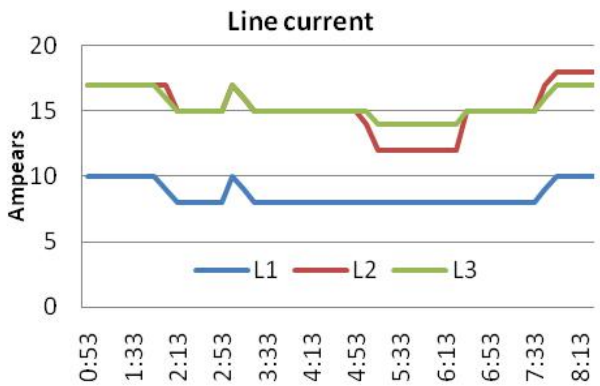

Figure-16. Variation in line currents.

d) Case-IV [Switching Sequence; S3 → S1 and S2 simultaneously]

Table-5 gives the switching instants of three induction generators under this case study.

Table-5. Switching instants in case -IV.

Particulars	Switching instant
No GCIG in grid	Before 2:09s
GCIG 2 switched in	2:09s
GCIG 1 and 3 switched in	3:39s
GCIG 1 and 3 switched off	4:49s
GCIG 2 switched off	5:39s

Figure-17 to Figure-21 shows the experimental observations for total current harmonics distortion (THD A) in three lines, total voltage harmonic distortion (THD V), reactive power drawn from grid, power factor at PCC and line currents at PCC.

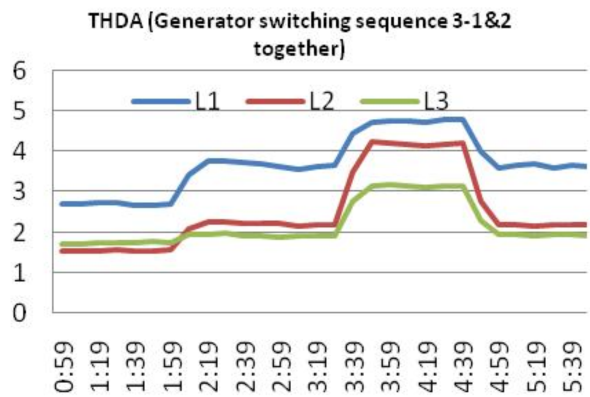

Figure-17. Total harmonic distortion in currents on three phases.

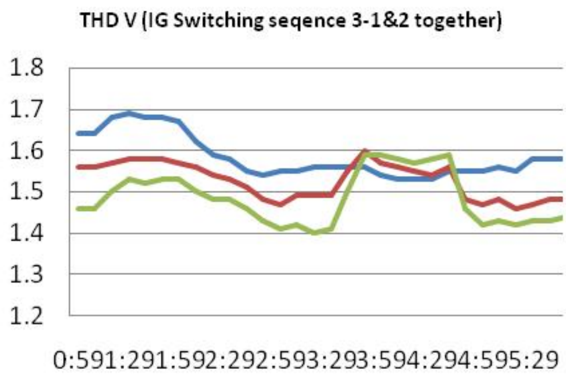

Figure-18. Total harmonic distortion in voltages on three phases.

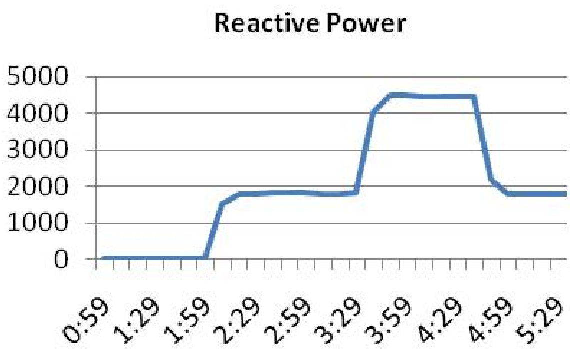

Figure-19. Variation in reactive power with switching of GCIGs.

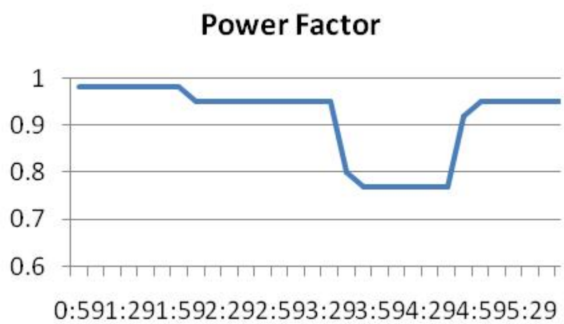

Figure-20. Variation in power factor with switching in of three GCIGs.

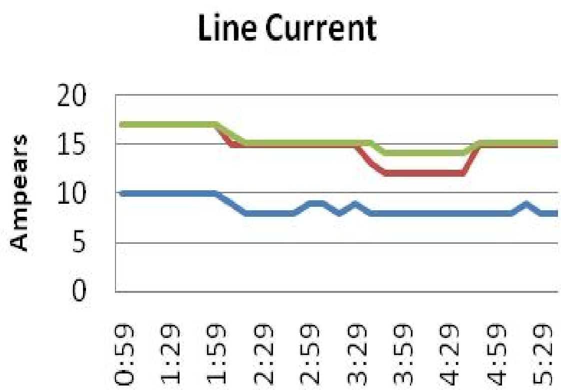

Figure-21. Variation in line currents.

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e) Case-V [Switching Sequence; S1, S2 and S3 all simultaneously]

All the three generators are switched in at the same time i.e. t = 1:33. Switching off sequence is again same i.e. GCIG1, 2 and 3 switched off simultaneously 3.13s. Figure-22 to Figure-26 shows the experimental observations for total current harmonics distortion (THD A) in three lines, total voltage harmonic distortion (THD V), reactive power drawn from grid, power factor at PCC and line currents at PCC.

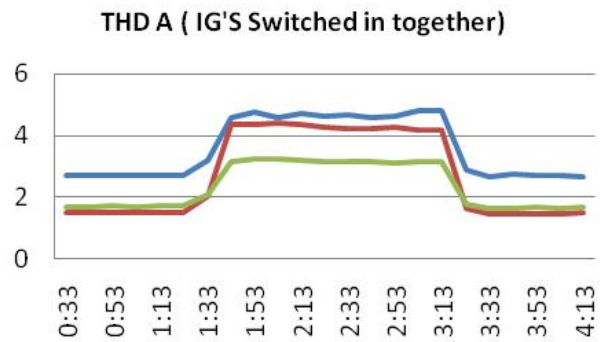

Figure-22. Total harmonic distortion in currents on three phases.

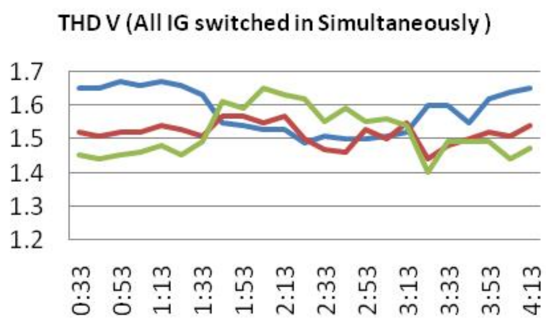

Figure-23. Total harmonic distortion in voltages on three phases.

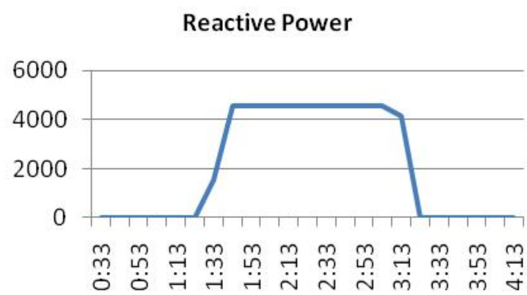

Figure-24. Variation in reactive power with switching of GCIGs.

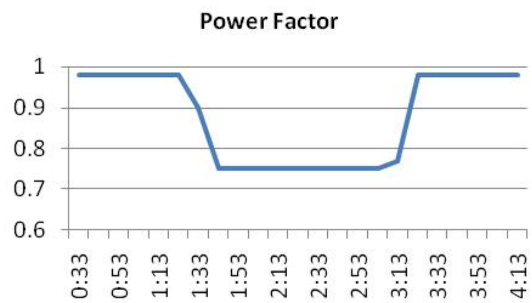

Figure-25. Variation in power factor with switching in of three GCIGs.

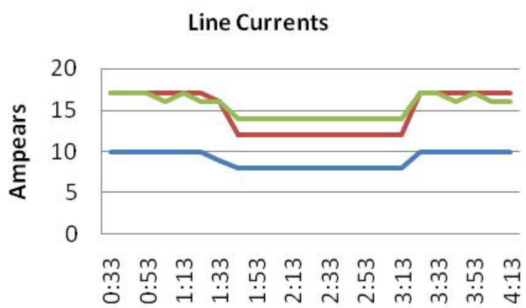

Figure-26. Variation in line currents.

4. RESULTS AND DISCUSSIONS

Table-6 to Table-10 gives the comparison between THD A, THD V, Reactive power and power factor with different sequences of switching.

Case-I [Switching Sequence 1-2-3]

Table -6.

Particulars	THD A			THD V			VAR	P.F.
	L1	L2	L3	L1	L2	L3		
No GCIG in grid	2.54	1.44	1.63	1.68	1.51	1.47	21	0.98
GCIG 1 switched in	2.88	1.69	1.71	1.66	1.55	1.46	659	0.97
GCIG 2 switched in	3.62	2.67	2.25	1.54	1.53	1.51	2450	0.92
GCIG 3 switched in	4.69	4.46	3.14	1.55	1.68	1.70	4498	0.75

Case-II [Switching Sequence; S1→ S2 and S3 simultaneously]

Table -7.

Particulars	THD A			THD V			VAR	P.F.
	L1	L2	L3	L1	L2	L3		
No GCIG in grid	2.58	1.52	1.62	1.63	1.57	1.44	26	0.98
GCIG 1 switched in	2.87	1.68	1.65	1.52	1.53	1.40	664	0.97
GCIG 2 and 3 switched in	4.63	4.02	2.99	1.54	1.72	1.60	4662	0.73

Case-III [Switching Sequence; S2→S1 and S3 simultaneously]

Table -8.

Particulars	THD A			THD V			VAR	P.F.
	L1	L2	L3	L1	L2	L3		
No GCIG in grid	2.73	1.53	1.75	1.69	1.55	1.45	16	0.98
GCIG 2 switched in	3.89	2.3	2.08	1.48	1.33	1.42	1847	0.95
GCIG 1 and 3 switched in	4.73	4.42	3.18	1.48	1.41	1.58	4626	0.74

Case-IV [Switching Sequence; S3→S1 and S2 simultaneously]

Table -9.

Particulars	THD A			THD V			VAR	P.F.
	L1	L2	L3	L1	L2	L3		
No GCIG in grid	2.7	1.56	1.75	1.67	1.57	1.53	17	0.98
GCIG 3 switched in	3.64	2.18	1.89	1.56	1.49	1.41	1813	0.95
GCIG 1 and 2 switched in	4.78	4.24	3.14	1.55	1.56	1.59	4487	0.77

Case-V [Switching Sequence; S1, S2 and S3 all simultaneously]

Table -10.

Particulars	THD A			THD V			VAR	P.F.
	L1	L2	L3	L1	L2	L3		
No GCIG in grid	2.71	1.5	1.73	1.66	1.53	1.45	15	0.98
GCIG 1,2 and 3 switched in	4.79	4.16	3.15	1.51	1.5	1.56	4569	0.75

Case-I: When sequence of switching is 1-2-3 no significant change is observed in THD V and remained less than 2% but THD A is increased from 2.54% to 2.88% in L1, from 1.44% to 1.69% in L2 and 1.63% to 1.71% in L3 after switching in of IG 1. When second GCIG is switched in an increase is observed; 3.62% in L1, 2.67% in L2 and 2.25% in L3. THD A goes to maximum value of 4.69%, 4.46% and 3.14% when all the three GCIGs are operational. The change in reactive power demand from the grid is also observed and found increasing with no of GCIGs in the circuit. Reactive power drawn from the grid is increased from 19 VAR to 659 VAR after switching of GCIG no 1; 659 VAR to 2450 VAR after switching of GCIG no 2 and 2450 VAR to 4498 VAR after switching of GCIG3. Power factor also decreased from 0.98 to 0.97 to 0.92 to 0.75 at the three instants. Before switching of GCIGs the currents drawn from the grid are L1 = 10A; L2 = 17A and L3 = 16 A and reduced to 9A; 16A and 16A after Switching in of IG1. Further current reduced to 8A; 14A and 15A after Switching in of IG2 and to 8A; 12A and 14A after Switching in of IG3. This reduction is due to the presence of induction generators now feeding some part of the load current.

Case-II: When only GCIG1 is in circuit THD A are 2.87% in L1, 1.68% in L2 and 1.65% in L3 and increases to 4.63% in L1, 4.02% in L2 and 2.99% in L3. VAR is also increased from 26 VAR to 4662 VAR and P.F. drops from 0.98 to 0.73.

Case-III: When IG2 was in circuit THD A is 3.89%, 2.3%, 2.08% and increased to 4.73%, 4.42% and 3.18% in L1, L2 and L3 respectively. VAR increases from 16 to 1847 and finally to 4626 and p.f. drops from 0.98 to 0.74.

Case-IV: When GCIG 3 inserted first and then 1 and 2 simultaneously, THDA increased from 2.7% to 3.64% and finally to 4.78%; 1.56% to 2.18% and then to 4.24%; 1.75% to 1.89% and to 3.14% in L1, L2 and L3 lines respectively. VAR increased from 17 to 4487 and p. f. drops from 0.98 to 0.77.

Case-V: When three IGs are started at once a sharp increase is seen in VAR from 15VAR to 4567 VAR. Power factor 0.98 to 0.75 and THD A from 2.71% to 4.79%, 1.5% to 4.16% and 1.73% to 3.15%. No significant change is seen in voltage and frequency. Flicker also remains within specified limits.

5. CONCLUSIONS

Analysis of experimental observations as obtained leads to the following major conclusions:

- In all the five cases under study reactive power consumption increases with increase in number of GCIGs in the circuit. Hence there is need to compensate this effect in case number of induction machines increases;
- For all the five cases the total harmonics distortion (voltage) is less than 2% which in is well below the 8% as per standards;
- There is increase in total harmonics distortion (current) with number of GCIGs increasing in the circuit;
- A sharp increase is seen in reactive power requirements from grid when machines are switched in simultaneously;
- Higher current harmonics distortion is seen in the lines which are lightly loaded. Therefore there is necessity to keep the load perfectly balanced;
- No significant change is seen in frequency and voltage variations; and
- Power factor also drops to significantly with more number of GCICs in the grid.

From the analysis as given above it may be concluded that an increase in number of machines causes the power quality problems mainly in current harmonics, reactive power and power factor. These problems will be more severe in weak grids. It is also observed that the simultaneous switching operation of induction generators results into excessive inrush of reactive power from grid, which is undesirable.

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