FLICKER CONTRIBUTION OF INDUCTION GENERATORS IN WIND ENERGY CONVERSION SYSTEMS

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Abstract *This paper gives a focus on the flicker emission by induction generators (IG) generally used in wind energy conversion systems. MATLAB based SIMULINK models are developed to investigate the effects when IGs are operating under self and grid connected mode. Simulated results as obtained are used to investigate the flicker emission in single and multi-machine operation. It also includes the effect of switching sequences of incoming generators on flicker emission in case of multi-machine operation.*

Keywords: *Flicker; Induction generator; Power quality; Wind generation; SIMULINK model.*

1. INTRODUCTION

Flicker is one of major parameter affecting the power quality of induction generators. Wind power plants produces Flicker emission due to fluctuation in the power output of wind generator due to variations in wind speed, effect of tower shadow and wind shears. The wind which is the driving force is varying continuously and results into flicker emission which leads to the power quality problem. Flicker produced by induction generators propagate from Point of common coupling (PCC) to customer premises through transformers, series compensators and transmission/ distribution lines. The flicker emission from a single or multi turbines wind generating systems may be assessed from the recommendations in IEC 61400-3-7 and IEC 61400-21. According to standard EN 50160, long term flicker limit required has to be less or equal to 1.0 during 95% of a week. Hence wind energy conversion systems need to be investigated regarding flicker emission. The flicker meter for measurement of flicker is given in IEC/ IEEE standard and same is used by many researchers [1]. Leonard et al [2] presented a discrete model of a flicker meter as per the IEC Standard. The model was used alone or in combination with SIMULINK SimPowerSystems block set, for measurement of flicker. The model parameters were taken for flicker measurement in 60 Hz system. Bertola et al [3] developed flicker meter model in MATLAB/ SIMULINK environment and validated for flicker emission studies.

Roohollah et al [4 & 5] used different software's to model electrical, mechanical and aerodynamic parts of wind energy conversion systems for power quality studies with main focus on flicker emissions for a wind power plant having large number of wind generators as well as for a standalone system operating with diesel generator. MATLAB/ SIMULINK software was used to model the electrical systems. Cai [6] aimed his research work to improves the conventional flicker measurement methods and with more types of lamps. Payam et al [7] proposed a simple method to study the source of flicker in a power system. It was easy to implement this system in measuring instruments. Wang et al [8] showed the measured values of flickers generated by a commercial wind power generation system in Taiwan. It was found from the measured results that ΔV_{10} flickers contributed by four WTIGs were well below the standard values. Hsu et al [9] investigated the flicker emission during high power outputs and also presented the relation between two short term severity indexes i.e. ΔV_{10} and P_{st}. Papadopoulos [10] investigated flicker emission considering different types of wind turbines, operating conditions, network characteristics and loading etc. The flicker index was given by modeling and implementing the algorithm for calculation of flicker. Van et al [11] analyzed the factors effecting the flicker emission. The flicker induced by the operation of grid-connected wind turbines was estimated using SVR. The PSIM software and MATLAB programme were used to obtain the short term flicker severity.

In this paper IEC/ IEEE flicker meter is used in MATLAB/ SIMULINK to study the flicker emission due to any change in the operating conditions of induction generators. The impact of change in wind speed, load, compensating capacitors and switching operations on flicker emission are investigated. For the first time, a sinusoidal signal has been considered to account any disturbance in the wind speed. Single and multi-machine operation under Self excited mode and grid connected mode are investigated.

2. THE FLICKER METER

The flickers can be considered as a low- frequency modulation of the network voltage at 50 Hz. The flicker-meter is an instrument which is used to separate the carrier wave from the modulating wave. It weights the effects of the latter based on human sensitivity to the disturbance, and generate the instantaneous sensation of the flicker. According to IEC/IEEE standards, the flicker severity can be of two types i.e. short-term value, P_{st}, measured over 10 minutes period, or a long term value, P_{lt}, calculated from a sequence of P_{st} over a period of 2 hours. P_{st} can be expressed as:

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_1 + 0.0657P_3 + 0.28P_{10} + 0.08P_{50}} \ldots (1)$$

In equation (1) the percentiles $P_{0.1}$, P_1, P_3, P_{10}, and P_{50} are the flicker levels exceeded for 0.1, 1, 3, 10, and 50% of the time during the period under observation. The cumulative probability function gives the exceeded flicker levels. Long term flicker emission is calculated from 12 consecutive P_{st} values (i.e. for two hours duration) as per the following formula:

$$P_{lt} = \sqrt[3]{\frac{1}{12} * \sum_{j=1}^{12} Pst_j^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

IEC/IEEE standards based flicker meter model is developed in MATLB/SIMULINK and is used in this paper, as used by some of the researchers [1, 3, 4 & 5]. The IEC/IEEE flicker meter as shown in figure 1 may be represented via block diagram as shown in figure 2 comprising of five sub blocks. Figure 3 shows the SIMULINK model of flicker meter as discussed above and the same is implemented to investigate the flicker emission in a wind energy conversion system.

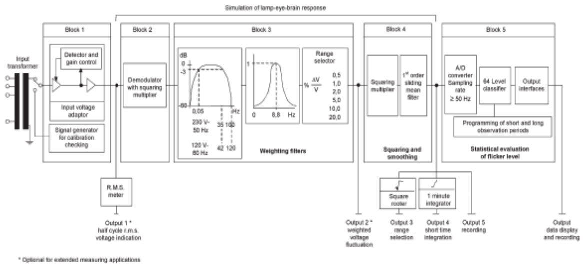

Fig. 1 IEEE flicker meter

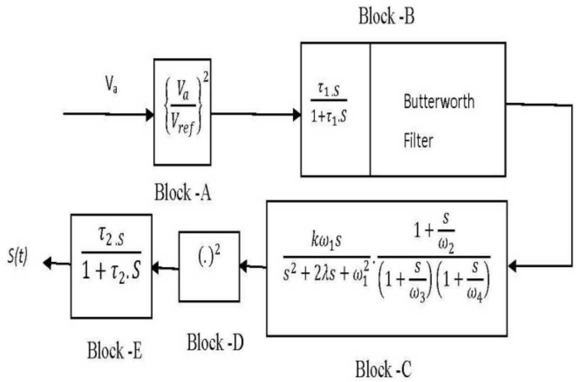

Fig.2 Block Diagram of IEEE flicker meter

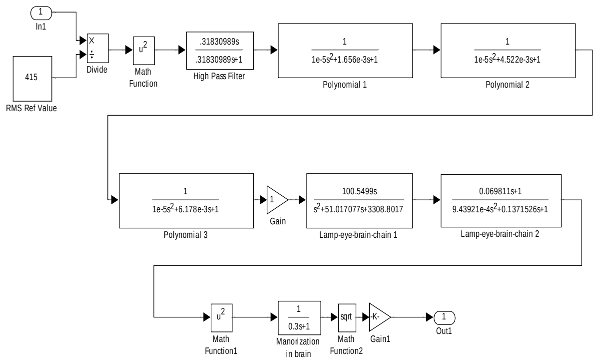

Fig. 3 SIMULINK model of flicker meter

3. FLICKER CONTRIBUTION OF SELF EXCITED INDUCTION GENERATORS

3.1 Single machine system

Figure 4 shows the MATLAB/ SIMULINK model of a self excited induction generator along with IEEE flicker meter as discussed in section II. In this model the wind variations are created by a modulated wave as shown in figure 5. As shown wind speed variations including the duration of change is possible by controlling the magnitude & frequency of the modulated wave. Table 1, shows the simulated results on a 160 kW, 400V, 50 Hz, 4-pole induction generator [Appendix I].

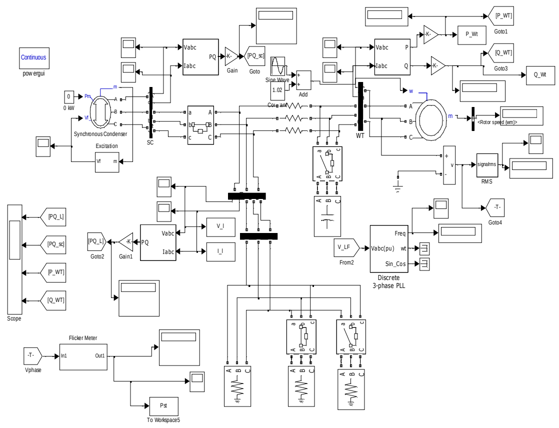

Fig. 4 SIMULINK model of SEIG for flicker study

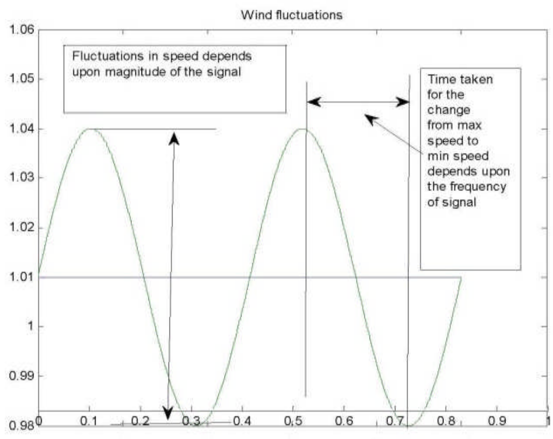

Fig. 5 Variations in wind speed

Table -1 Flicker emission by SEIG due to change in magnitude and rate of change of wind speed variations

Rate of change of Wind Speed	Wind Speed Variations		
	0.99 pu to 1.05pu	0.97 pu to 1.07 pu	0.92 pu to 1.12 pu
	Instantaneous Flicker Emission		
2 Hz	0.02055	0.03151	0.06062
5 Hz	0.04211	0.06930	0.13920
10 Hz	0.06361	0.10530	0.21120
15 Hz	0.03865	0.06320	0.12600
20 Hz	0.02562	0.04078	0.08035
25 Hz	0.01905	0.02906	0.05598

Table 1 shows the variations in instantaneous flicker emission with change in speed and magnitude of wind variations. It is observed that;

- For a given range of wind speed variations instantaneous flicker first increases with rate of change of (frequency) wind speed variations and then again start decreasing. This gives a critical value of frequency of wind speed variations i.e. 10 Hz, which results into the maximum value of flicker.
- For a given value of rate of change of (frequency) wind speed variation, flicker at machine terminals increases with increase in the range (magnitude) of wind speed variations.

The effect of capacitor banks used for compensation & switching of capacitor bank are investigated for instantaneous flicker emissions and are tabulated in table 2.

Table-2 Effect of capacitor value and capacitor switching on instantaneous flicker emissions

Particulars	Capacitor Bank no1 (kVAR)	Capacitor Bank no2 (kVAR)	Load (kW)	Inst flicker	Ter. Volt	Frequency
Single value capacitor bank at start	150	0	0	0.2093	210.5	50.83
Single value capacitor bank at start	150	0	160	0.1639	187.5	50.42
Single value capacitor bank at start	180	0	160	0.2112	210.4	50.42
Capacitor bank no1 at start and capacitor bank no 2 at 1sec	150	30	160	0.2101	205.3	50.47
Capacitor bank no1 at start and capacitor bank no 2 at 1sec	30	150	160	0.1904	203.0	50.46

It is observed from the above table that flicker emission which is dependent upon the terminal voltage varies due to any change in the compensating capacitor bank. This shows that the flicker emissions may be controlled by appropriate selection of capacitor bank along with its switching instant.

3.2 Multi-machine system

Multi machine model of self excited induction generators feeding a resistive load for investigating flicker emission is shown in Fig. 6. Three wind generators of 160 kW, 75kW and 7.5 kW [Appendix -I] capacities are used for investigating the flicker emission due to switching. The synchronous condenser is used for initial voltage buildup in the SEIG's. The different switching sequences for incoming machines as considered are tabulated in table 3.

Table - 3 Switching sequences for SEIG of different ratings

Switching Details	Sequ no
160kW at start, 75kw at 1 sec, 7.5 kW at 2 sec	1
7.5 kW at start, 75kw at 1 sec, 160 kW at 2 sec	2
75 kW at start, 7.5kw at 1 sec, 160 kW at 2 sec	3
All machines simultaneously at start	4

All sequences as per table -3 results into the same value of flicker emissions as given below:

i. Magnitude = 0.1pu, frequency = 3Hz flicker = 0.10680
ii. Magnitude = 0.1pu, frequency 10Hz flicker = 0.26620
iii. Magnitude = 0.1pu, frequency 25Hz flicker = 0.07004

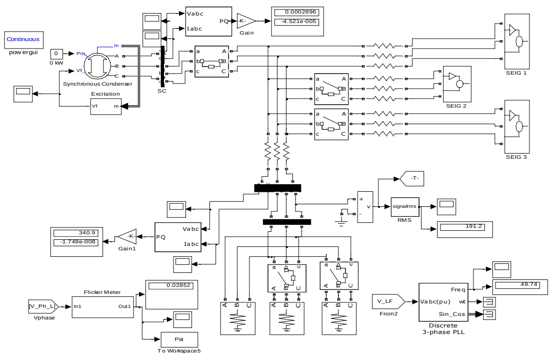

Fig. 6 Simulink model of SEIG multi- machine system

4 FLICKER CONTRIBUTION OF GRID CONNECTED INDUCTION GENERATOR

As the voltage and frequency are controlled by grid in case of stiff grid, hence in single or multi-machines operation no change in voltage or frequency is observed at point of common coupling (PCC). Since flicker is the phenomenon related with voltage variations, hence no flicker appears in strong grids. The programmable voltage source is used a stiff grid having short circuit ratio of $100*10^6$ and X/R ratio of 7.

4.1 Single machine system connected to weak grid:

The SIMULINK model of single machine connected to weak grid for flicker investigation at varying wind is shown in Fig.7. In this model the weak grid is created using voltage source block and the of the weak grid's short circuit ratio is taken as $10*10^5$ and X/R ratio is 1. The instantaneous flicker emission is observed with wind variations at different rates. 160kW induction generator [Appendix –I] is inserted in the circuit at 0.5 sec after start of simulation.

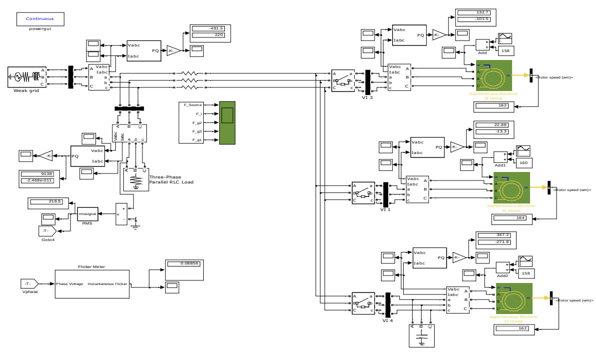

Figure. 7. SIMULINK model of grid connected multi machine system for flicker study

Table-4 Instantaneous flicker emission by GCIG connected to weak grid

Rate of Change of wind variations	Magnitude of wind variation		
	0.03 pu	0.05 pu	0.1 pu
	Instantaneous Flicker emissions		
2 Hz	0.03665	0.06450	0.09409
3 Hz	0.03427	0.06274	0.10840
5 Hz	0.03392	0.05728	0.11000
10 Hz	0.03875	0.06334	**0.11690**
15 Hz	0.02154	0.03532	0.06800
25 Hz	0.00967	0.01533	0.02968

Table 4 gives the instantaneous flicker emissions by GCIG connected to a weak grid with different magnitudes & rates of wind variations. Analysis of this table yields the same observations as in case of SEIG (Table 1). This also gives a critical value of frequency of wind speed variations i.e. 10 Hz, which results into maximum value of flicker.

4.2 Multi-machine system connected to weak grid:

Three machines of same rating: Simulated results of three different switching sequences for low, medium and strong wind variations are investigated for three machines of 75 kW are operating in weak grid is shown in table 5.The Fig. 8 to Fig. 10 shows the flicker emission, load terminal voltage and frequency at load terminals for the worst case of flicker emissions (without capacitor bank).

Table- 5 Instantaneous flicker emission by GCIG of same rating with different switching sequences

Switching Details	Switching Sequ no	Instantaneous flicker emissions		
		Magnitude = 0.1 rate of change of wind variations =3 Hz	Magnitude =0.1 rate of change of wind variations = 10 Hz	Magnitude=0.1 rate of change of wind variations = 25 Hz
75 kW at start, 75kw at 0.5 sec, 75 kW at 1sec	1	0.09899	0.08917	0.03672
75 kW at start, and two IG of 75 kW each at 0.5 sec	2	0.09893	0.09012	0.03289
All machines of 75 kW each, switched on simultaneously	3	0.09970	0.09075	0.03488
		With additional capacitor bank of 130kVAR at the terminals of one machine		
		0.1272	0.1436	0.8296

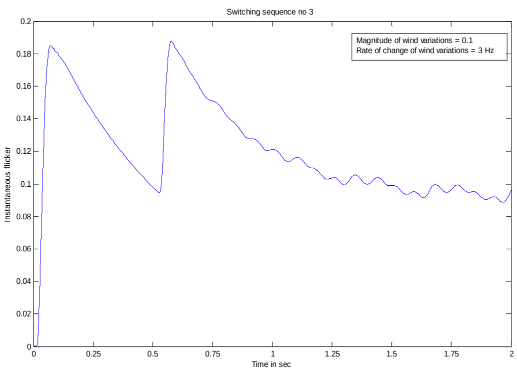

Fig.8 Instantaneous flicker emissions when three machines of same rating switched on simultaneously at 0.5 sec

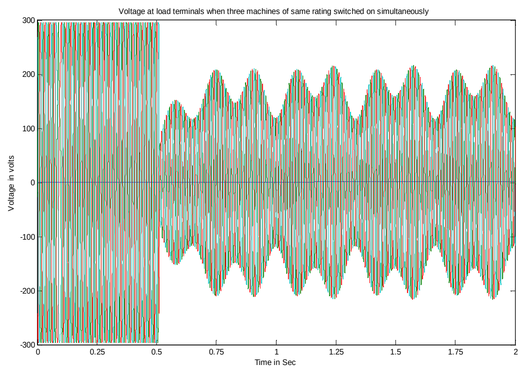

Fig.9 Terminal voltage when three machines of same ratings switched on simultaneously at 0.5 sec

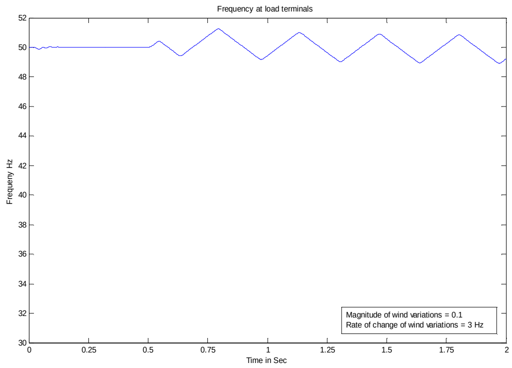

Fig.10 Frequency at load terminals when three machines of same rating switched on simultaneously at 0.5 sec

From the table 5 and Fig. 8 to Fig. 10, it is observed that:

- Maximum flicker emission occurs when all the machines are switched on simultaneously.
- Lowest flicker emissions are seen at switching sequence -2, with wind variation frequency 25 Hz and magnitude of 0.1 pu.
- The use of capacitor to improve the voltage also results in increased flicker emission as the highest flicker emissions appears at sequence 3 when a capacitor bank of 130 kVAR is connected at the terminals of machine -III
- Terminal voltage as shown in Fig. 5.25 is reduced to a low value than the rated value.
- Variations in the frequency are also observed.

Three machines of different rating: In this case three induction generators of different ratings i.e. IG no 1 is of 110 kW, IG no 2 is of 75 kW and IG no 3 is of 37 kW are considered. The total capacity of the farm is almost same as with three machines of same rating. The flicker emissions at three different types of wind variations for seven different switching sequences is investigated and tabulated in table 6. Fig. 11 to Fig.13 shows the variations in above parameters when capacitor bank of 130 kVAR is connected at the IG –III terminals.

Table-6 Instantaneous flicker emission at different switching sequences (Three machines of 110kW, 75kW and 37 kW)

Switching Details	Sequ nos	Instantaneous flicker emissions		
		Magnitude of wind variation=0.1 Rate of change of wind variations = 3 Hz	Magnitude of wind variation=0.1 Rate of change of wind variations = 10 Hz	Magnitude of wind variation=0.1 Rate of change of wind variations = 25 Hz
110 kW at start, 75kW at 0.5 sec, 37 kW at 1sec	1	0.09633	0.08978	0.03263
75 kW at start, 37 kW at 0.5 sec, 110 kW at 1sec	2	0.09665	0.09150	0.04182
37 kW at start, 110 kW at 0.5 sec, 75 kW at 1sec	3	0.09674	0.09069	0.04309
37 kW at start, 110 kw and 75 kW at 0.5 sec	4	0.09696	0.09170	0.03480
75 kW at start, 110 kw and 37 kW at 0.5 sec	5	0.09652	0.09132	0.03351
110 kW at start, 37 kw and 75 kW at 0.5 sec	6	0.09628	0.09090	0.03230
All machines switched on simultaneously	7	0.09732	0.09194	0.03545
		With additional capacitor bank of 130 kVAR connected at the terminals of IG -III		
		1.22	1.79	1.07

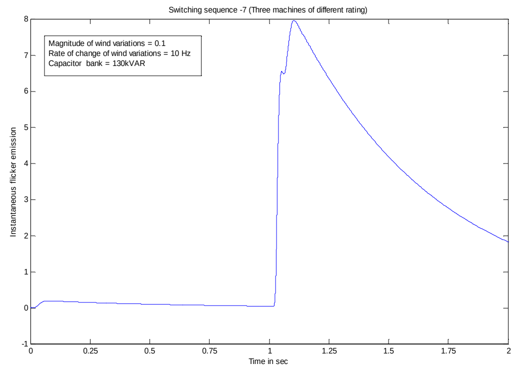

Fig.11 Instantaneous flicker emissions when three machines of different ratings switched on simultaneously at 1.0 sec with 130 kVAR capacitor bank at terminals of IG –III

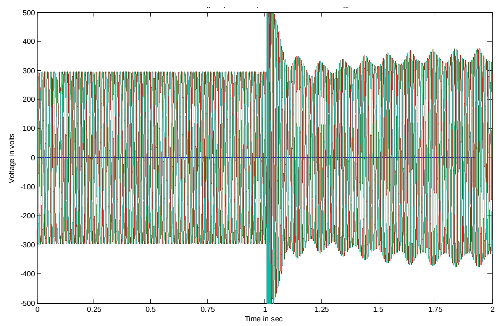

Fig. 12 Voltage at load terminals when three machines of different ratings switched on simultaneously at 1.0 sec with 130 kVAR capacitor bank at terminals of IG -III

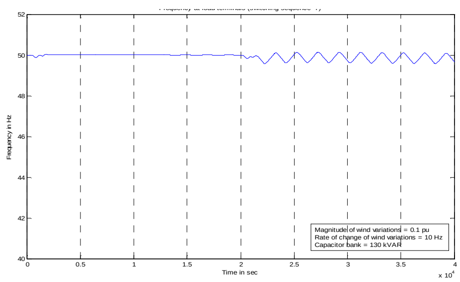

Fig. 13 Frequency at load terminals when three machines of different ratings switched on simultaneously 1.0 sec with 130 kVAR capacitor bank at terminals of IG-III

The switching sequence no 7 gives the maximum value of instantaneous flicker emissions. At this switching sequence the terminal voltage is found reduced than rated value. Variations in the frequency are also recorded.

When a capacitor bank of 130 kVAR is used at the terminals of IG –III to improve the voltage profile at load terminals, large increases in flicker emission is seen. It is also observed that the flicker emission has crossed the standard value of flicker emissions. But simultaneously the voltage profile at load terminals as shown in Fig.12 is found improved. It also results into an improvement in frequency variation

5 DISCUSSIONS

This paper includes discussions related to one of the major power quality issue i.e. flicker. For such investigations IEEE standard based flicker meter is used. SIMULINK models as listed below includes the wind variation representation through a modulated wave of sinusoidal form

- SIMULINK model of SEIG(single machine and multi machine operation)
- SIMULINK model of GCIG(single machine and multi machine operation)
  a. Connected to stiff grid
  b. Connected to weak grid

Analysis of simulated results as discussed in the chapter yields following conclusions;

1. **SEIG (single machine operation)**
   - For a given range of wind speed variations instantaneous flicker first increases with rate of change of (frequency) wind speed variations and then again start decreasing. This gives a critical value of frequency of wind speed variations i.e. 10 Hz, which results into the maximum value of flicker.
   - For a given value of rate of change of (frequency) wind speed variation, flicker at machine terminals increases with increase in the range (magnitude) of wind speed variations.
   - Flicker emission which is dependent upon the terminal voltage varies due to any change in the compensating capacitor bank. This shows that the flicker emissions may be controlled by appropriate selection of capacitor bank along with its switching instant.
2. **SEIG (multi- machine operation)**
   - Magnitude and rate of change of wind speed effects the flicker emissions.
   - Switching sequence has no effect on flicker emission.
3. **GCIG (connected to stiff grid)**
   - Due to presence of stiff grid, no effect on flicker emission.
4. **GCIG (single machine connected to weak grid)**
   - Same effects as discussed in case of SEIG as single machine.

5. GCIG (multi- machine connected to weak grid)

- Magnitude and rate of change of wind speed effects the flicker emissions.
- Maximum flicker emissions occur when all the machines are switched on simultaneously.
- The use of capacitor to improve the voltage also results in increased flicker emissions.
- Terminal voltage falls to a low value
- Variations in frequency are observed.

6 CONCLUSION

From the above discussions, it may be concluded that the operation of any machine (single machine/ multi-machine operation) will lead to a severe flicker in case it is subjected to wind variations of 'large magnitude and frequency of variations close to critical value'. In addition high value of flicker may be avoided by suitable selection & switching of compensating capacitors. Simultaneous switching of number of machines in a wind farm may lead to flicker problem

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APPENDIX –I: Parameters of machines used for simulation.

Machine Rating (kW)	Stator Resistance (R_s) pu	Rotor Resistance (R_r) pu	Stator leakage inductance (L_s) pu	Rotor leakage inductance (L_r) in pu	Mutual Inductance (L_m) in pu
160	0.01379	0.007728	0.04775	0.04775	2.416
110	0.01481	0.008464	0.04881	0.04881	2.241
75	0.01665	0.009804	0.04933	0.04933	2.224
37	0.01904	0.011630	0.05260	0.05260	1.970
7.5	0.03461	0.034700	0.04484	0.04484	1.827