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Voltage and Current Control Strategy for Grid Connected WECS Employing Two and Three Level Voltage Source Converters

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Abstract. This paper presents voltage and current control strategy for grid connected variable speed wind turbine induction generator employing two and three level voltage source inverters. Induction generators are widely used because of its low cost, robust construction and capability of feeding active power to load without getting reactive power from separate source. The mechanical energy required to drive the generator is obtained from a variable speed wind turbine. Three phase induction machine is excited from a three phase voltage source converter. The DC voltage of the capacitor is inverted and fed to the three phase grid using a current controlled voltage source inverter. Control strategy has been developed for maintaining the DC link voltage constant and also to feed the power at unity power factor to the grid, even though there is variation in wind speed. It is also shown that the harmonics are considerably reduced when a two level inverter is replaced by a three level inverter. The simulation study has been carried out using MATLAB/Simulink. Simulation results indicate the feasibility of control strategy.

Key words

Wind energy conversion systems(WECS), Induction generator(IG), Voltage source converter(VSI), Current controlled voltage source inverter (CCVSI), Pulse width modulation(PWM).

1. Introduction

Energy is an inseparable part of every human activity. It exists in different forms and can be converted from one form to another based on the need. Energy production is always less than the demand. At the same time, the sheer intensity of energy production and use has begun to result in deleterious impacts on the environment through pollution. This has awakened people and governments to the problems of continuing energy supply expansions. As per the statistics given in [1], the world's energy supply mainly comes from fossil fuels. Since these are utilized to 75% of the total consumption, the rate of their depletion is exponentially increasing. Therefore it's now inevitable to search for a solution. In this process other systems based on non-conventional and renewable sources are being tried by many countries. These are solar, wind, sea, geothermal and biomass.

Wind energy uses high wind velocity available in certain parts. Wind energy is used for pumping water and for electricity generation. About 2 million wind pumps are in operation in different countries. A minimum wind speed of 3 m/s is needed. This is considered to have a high efficiency. Coastal, hilly and valley areas are considered to be favourable. According to Ministry of New and Renewable Energy, Gross Potential of India is estimated to be 48,561 MW and total capacity is 14,158 MW. Coastal areas of Gujarat, Maharashtra and Tamil Nadu are considered as favourable. A number of experimental stations have also been set-up.

Wind energy conversion systems (WECS) involve many fields of various disciplines such as kinematics, mechanics, aerodynamics, meteorology, power electronics, power systems, as well as topics covered by structural and civil engineering. The main objective of this paper is on study of various options available to us and their control while connecting a variable speed wind energy conversion system to a three phase grid. The increased emphasis on regulating the terminal voltage with the load and to utilize the machine to its rated capacity has accelerated research and development of WECS. WECS involves either Induction machines or Synchronous machines for conversion of mechanical energy into electrical energy (as an electromechanical device). In this paper a squirrel cage induction machine is used as a energy conversion device for the study. In some literatures, studies are done using slip ring induction machines. WECS can be either self excited or grid connected. Most of the WECS are grid connected. The work presented in this paper is focused on the study of grid connected WECS.

A number of methods have been proposed in the literature. G. V. Jayaramaiah et al. [2] has presented voltage build up process in stand-alone IG, The induction machine is excited by a sine pulse width modulated two level VSI and the control strategy is so developed that the DC link voltage is always maintained constant irrespective of variations in the load. In the paper [3] modeling of variable speed wind turbines has been presented. Here low cost power converters are employed and the machine used for grid is synchronous machine. The possibility of the connection of low cost wind turbine generator (WTG) into existing low voltage grid and also the dynamic analysis has been carried out by changing wind velocity and connection-disconnection process has been discussed in the paper [4]. [5] demonstrates the increase in transient stability of grid by using a doubly fed induction generator(DFIG). It also discusses the behavior of DFIG in transient stability studies. A control scheme called feedback linearization technique has been applied to a grid connected WECS in [6] to regulate electrical and mechanical parameters. It not discusses on linearization of non linear multiple input output systems.

Power electronics devices play a important role in WECS. With the advancements in technology, numerous industrial applications have also begun to require higher power apparatus in recent years. A high power and high voltage applications makes use of a multilevel power converter structure as an alternative. A multilevel converter not only achieves high power ratings, but also reduces harmonic content and THD value [7]. Renewable energy sources can be easily interfaced to a multilevel converter system for a high power application [7] [8].

In this paper a comparison study of WECS employing two and three level(diode clamped) VSI is modeled and it is shown that the three level inverter employed WECS leads to better power quality over two level inverter employed WECS.

2. Description of the system

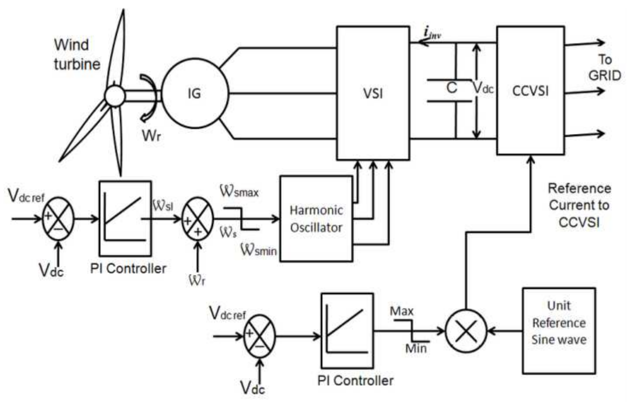

Fig1. System Block Diagram

Referring to fig 1, the three phase induction machine is driven by a variable speed wind turbine. The velocity of the wind drives the shaft of the induction machine with a speed as adjusted by the gear ratio. The terminals of induction machine are connected to a 3 phase converter with a DC side capacitor. The initial voltage across the capacitor is provided from a 12V battery [2].

This capacitor is connected to a current controlled voltage source inverter (CCVSI) and the CCVSI is in turn interfaced with the grid. Here the grid voltage is maintained at 100V and the grid frequency is 50Hz. Thus the sine PWM VSI and the CCVSI form the back to back connection.

The necessary magnetizing ampere turns required for the initial excitation is provided by the initial voltage of the capacitor. Thus care has to be taken that the initial voltage of the capacitor should be sufficient to magnetize the air gap of the induction machine. This voltage across the DC is first inverted to AC via three phase inverter and fed to the induction machine. Once the system gets energized, generator mode is set into action, and thus the system starts sourcing the power. This AC voltage is now rectified and the capacitor starts charging. The DC link voltage increases to a reference value. Control strategy has been developed to maintain this DC link voltage constant. This actual value of DC link voltage of the capacitor is continuously compared with the reference value. The error obtained is the difference of actual capacitor voltage and the reference, which indicates the deviation of the actual DC voltage with the expected reference voltage. This error is processed by a PI controller. Based on the polarity and magnitude of error signals, PI controller suitably sets the slip frequency of the machine. The stator frequency is obtained after adding the output of PI controller to rotor frequency. This stator frequency is maintained between the limits using a limiter. It is then fed to a harmonic oscillator that generates three phase sine waves and compares it with a high frequency triangular wave. The output of harmonic oscillator are pulses to inverter switches. Hence a DC voltage is maintained across the capacitor. The reference voltage is 600V. A similar control strategy has been developed in [2] where the controlled variable is a stator frequency.
Once the DC link voltage reaches the reference, the system is connected to the grid via CCVSI. The difference of the actual value and the reference value of DC link capacitor is directly proportional to the magnitude of grid current. This error is given as an input to PI controller. The controlled signal on multiplying with a unit sinusoid forms the reference current to CCVSI. Any changes in the wind speed, changes the rotor speed and thereby grid current changes i.e., increase in wind speed increases grid current.

3. Modeling of Wind Turbine and Induction Machine

In this section we discuss mathematical modeling of wind turbine and Induction Machine.
All notations have their usual meaning.

A. Wind turbine

Wind turbine is characterized by the non-dimensional curve of coefficient of performance (C_p), as a function of tip-speed ratio(λ).

For modeling wind turbine, we define (C_p) as a approximated polynomial function of λ as given in (1).

$$C_p == 0.0043 - 0.1080\lambda + 0.146\lambda^2 - 0.0602\lambda^3 + +0.0104\lambda^4 - 0.0006\lambda^5 \quad (1)$$

Variation of C_p Vs λ is shown in fig 2. Betz limit states that the ideal wind turbine has an maximum efficiency of 57%, but fig 2 shows the peak value around to be 70% this is due to polynomial approximation of actual characteristics.

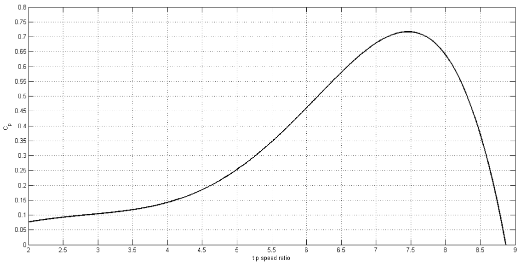

Fig2. Variation of C_p Vs λ

Tip speed ratio is a function of turbine radius(r), turbine speed(ω) and the wind velocity(v). Tip speed ratio equation is given by the equation

$$\lambda = \frac{r}{\omega v} \quad (2)$$

The output P_t of the wind turbine is calculated as

$$P_t = \frac{1}{2} C_p(\lambda)\rho A v^3 \quad (3)$$

Where ρ is the air density and A is the swept area of the wind turbine.
Variation of power with rotor speed for various wind speeds is shown in fig 3.

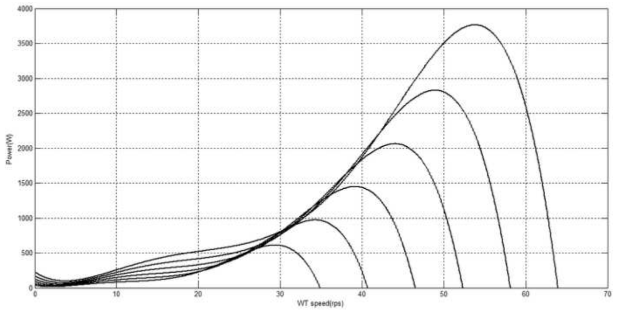

Fig 3. Variation of Power Vs Wind turbine speed

The torque developed by the wind turbine can be expressed as

$$t_t = \frac{P_t}{\omega} \quad (4)$$

Using equations (2), (3) and (4), torque equation can be written as

$$t_t = \frac{1}{2}\rho A r \frac{C_p(\lambda)}{\lambda} v^2 \quad (5)$$

The relation between mechanical torque (t_m) developed by the turbine and the input torque(t_t) to the generator is

$$t_m = \frac{t_t}{G} \quad (6)$$

The relation between angular velocity(ω_r) of the generator and the mechanical angular velocity (ω) is

$$\omega = \frac{\omega_r}{PG} \quad (7)$$

Wind turbine data necessary for simulation is provided in appendix and is taken from [10].

B. Induction Machine

Induction machine is modeled in the stationary dq-axis reference frame using standard notations given in [11][12].

$$\begin{bmatrix} \dot{\psi}_{ds} \\ \dot{\psi}_{qs} \end{bmatrix} = \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} - R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} \dot{\psi}_{dr} \\ \dot{\psi}_{qr} \end{bmatrix} = -R_r \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} - \omega_r \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \psi_{ds} \\ \psi_{dr} \\ \psi_{qs} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} \quad (10)$$

$$t_e = \frac{3}{2}\frac{P}{2}(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (11)$$

$$\dot{\omega}_r = \frac{P}{2J}(t_e - t_m) \quad (12)$$

4. Modeling of Voltage source converters

In this section mathematical modelling of two and three level voltage source converters, (CCVSI) and grid are discussed. Sine pulse width modulation technique is employed to generate pulses to both two and three level inverters.

A. Two Level Inverters

Using switching functions(S_a,S_b and S_c), expressions for inverter pole voltages(V_{ao},V_{bo} and V_{co}) and phase voltages(V_{an}, V_{bn} and V_{cn}) are given by

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{v_{dc}}{2} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} \quad (14)$$

Here (14) assumes balanced voltages.

B. Three Level Inverter

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \frac{v_{dc}}{2} \begin{bmatrix} S_{ao} + S_{a1} - 1 \\ S_{bo} + S_{b1} - 1 \\ S_{co} + S_{c1} - 1 \end{bmatrix} \tag{15}$$

Here (S_{ao},S_{a1}), (S_{bo},S_{b1}) and (S_{co},S_{c1}) are the switching functions (upper two switches of a leg) of a,b and c phases respectively.

In both cases, inverter current is given by

$$i_{inv} = S_a i_a + S_b i_b + S_c c \tag{16}$$

For a three level inverter

$S_a = S_{ao} + S_{a1}$; $S_b = S_{bo} + S_{b1}$ and $S_c = S_{co} + S_{c1}$

C. CCVSI and Grid

$$v_{dc} = \begin{cases} \int \left(i_{inv} - \frac{v_{dc}}{R} \right) \frac{-1}{C} & for\ v_{dc} > \ v_{ref} \\ \int (i_{inv} - i_{ccvsi}) \frac{-1}{C} & for\ v_{dc} < \ v_{ref} \end{cases} \tag{17}$$

The 3φ grid is modeled as an RLE load and is mathematically defined as follows

$$v_{ccvsi} = E_g + L_g i_g + L_g \frac{di_g}{dt} + R_g i_g \tag{18}$$

Where E_g is the grid voltage, I_g is the grid current, L_g is the inductance of the grid and R_g is the grid resistance.

5. Results and Discussion

In this section the performance of grid connected WECS is discussed for wind speed of 5m/s for both two and three level converters. It is shown that the ripple in electromagnetic torque developed by the machine and the harmonics in the grid side line voltage are considerably reduced when a two level converter is replaced by a three level converter. The DC link voltage is maintained at 600V in all the cases. The phase voltage of grid is maintained at 100V, just to prove that the proposed strategy is able to feed power to the grid. This value can be suitably changed to a required value.

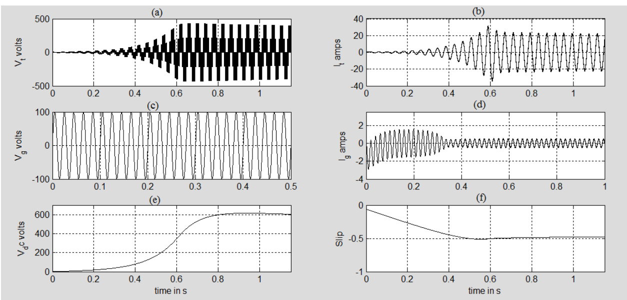

Fig 4. Grid connected system with SPWM two level inverter during transients

Fig 4 shows the transient behaviour results of grid connected system with SPWM two level inverter.Figures 4(a) and 4(b) shows the terminal voltage and the terminal current build up process. Fig 4(c) shows the grid voltage. The grid voltage is maintained at 100 V and the frequency is 50 Hz. Fig 4(d) is the grid current. The strategy developed here is to maintain a constant DC link voltage. Fig 4(e) shows the DC link voltage building process and at 1.2s a steady state value of 600 V is reached and this value is maintained henceforth. Fig 4(f) is the result of slip frequency. Since the induction machine is operated in generator mode, the slip is negative, which confirm the generator action.

A. Results of two level VSC

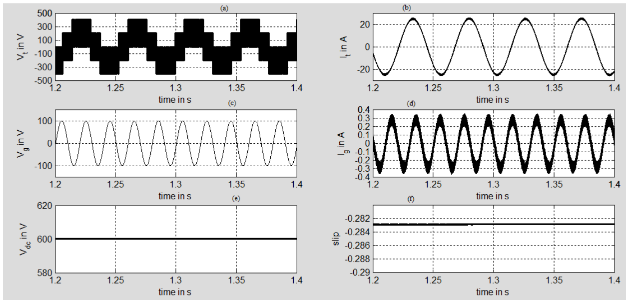

Fig 5. Grid connected system with SPWM two level inverter for wind speed of 5m/s

The results of Fig 5 are simulated for a wind speed of 5m/s. Fig 5(a) shows the constant terminal voltage of IG. The phase voltage of the IG terminal confirms that the inverter is a two level inverter. Fig 5(b) is the terminal (stator) current. The grid voltage is maintained at 100 V and the frequency is 50 Hz throughout the simulation time. Fig 5(d) is the grid current. Since the power is fed to the grid, at any point of time the power should be negative. In other words, the product of grid voltage and grid current at any instant should be negative and this can happen only if grid voltage and grid current are in phase opposition. Figures 5(c) and 5(d) clearly shows the phase opposition between grid voltage and grid current and thereby supporting the theory. The control strategy developed is to maintain a constant DC link voltage. The reference value of DC link voltage is set to 600 V and result in Fig 5(e) confirms the same by maintaining a DC link voltage of 600 V. The generator operation is verified by negative slip and its shown in Fig 5(f).

B. Results of three level VSC

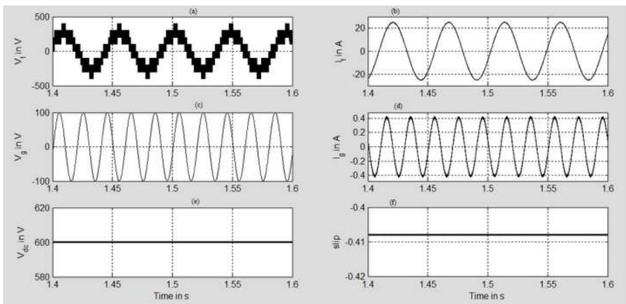

Fig 6. Grid connected system with SPWM three level inverter for wind speed of 5m/s

Fig 6 are the simulated results for the wind speed of 5m/s. Fig 6(a) is the terminal voltage of IG. The number of levels in the terminal voltage has increased, which approximates in a better way to a ideal sine wave than it was in case of two level inverter (Fig 5(a)). Comparing

Figures 5(b) with 6(b) we can clearly observe that the ripples have been considerably reduced in the latter case. Ripples in stator current has also been reduced. In all of the cases the grid voltage is maintained at 100V and frequency is 50Hz. Fig 6(c) is the grid voltage. Since the power is fed to the grid, there exists a phase opposition between grid voltage Fig6(c) and grid current Fig 6(d). Fig 6(e) is the constant DC link voltage maintained at 600V and the slip is negative and it can be seen from Fig6(f) with the value of -0.345

C. Electromagnetic Torque

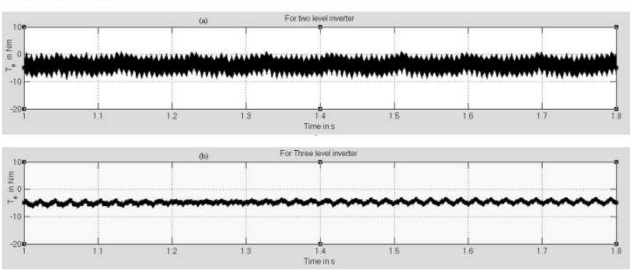

Fig 7. Ripple in the electromagnetic torque curve for two and three level inverter

Fig 7 shows the comparison of electromagnetic torques developed by IG feeding two and three level inverters. Fig 7(a) is the electromagnetic torque developed by IG feeding two level inverter. Figure 7(a) clearly indicates that there is a considerable ripple in the torque curve. However this ripple is reduced in Fig 7(b) by a considerable amount by using a three level inverter than a two level inverter, thus supporting the studied theory. Induction machine model with saturation is used for the simulation study.

D. Harmonic Analysis

Fig 8 shows the line voltage harmonic spectrum of two level inverter. The fundamental component appears at 50Hz which is the frequency of the voltage. It is seen that the triplen harmonics are absent, i.e., harmonics at 150Hz, 300Hz, 450Hz, 600Hz. are absent.Harmonics are dominant at 950Hz and 1150Hz which are at position of m_f-2 and m_f+2 where m_f is the modulation frequency. There are harmonics at $2m_f$-1 and $2m_f$+1 also. These results validate the theory presented in [13]. Here m_f is 21.

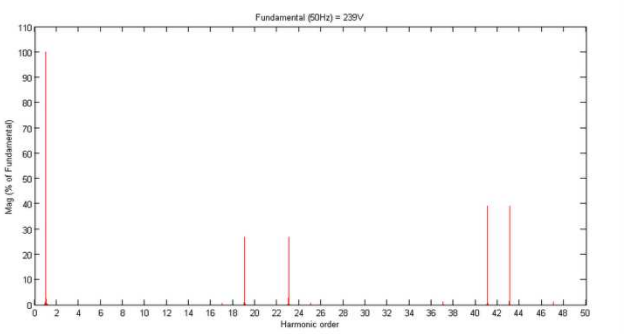

Fig 8. Harmonic spectrum of two level invertir

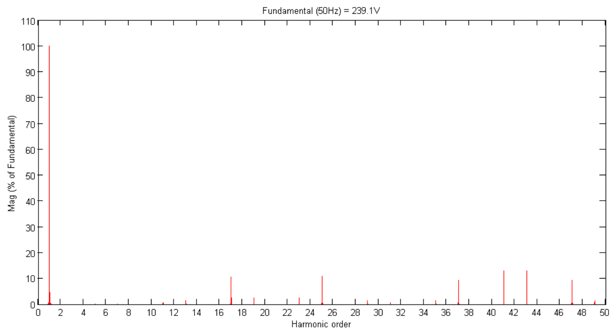

Fig 9. Harmonic spectrum of three level inverter

Fig 9 shows the line voltage spectrum of three level inverter. Even in this case fundamental component appears at 50Hz and triplen harmonics are absent. However it seen that a dominant harmonics are seen at the 850Hz(m_f-4) and 1250Hz(m_f+4), but there is a considerable reduction in the harmonic content. The results of the spectrum validate the theory presented in [14].

6. Conclusion

This work presents the voltage building process and DC link voltage control of grid connected squirrel cage induction generator (IG) driven by a variable speed wind turbine. Performance of WECS is studied using two and three level converters. In all these cases DC side of the inverter is connected to a capacitor with a small initial voltage. Control strategy for maintaining a constant DC voltage is studied. The grid current increases as the wind speed increases and the power is fed to the grid at unity power factor. Harmonic analysis has also been carried and WECS with three level inverter has lower harmonics than WECS with two level inverter.

The proposed scheme is mathematically modeled and simulated using MATLAB/SIMULINK. The simulated results validate the studied control strategy.

APPENDIX

Wind turbine specifications [10]
Air density ρ = 1.08 kg-m^{-3}
Radius r=5.525 m
Gear ratio G=5

IM Specifications[12]

Phase	03
Poles	04
Rated Power	03 HP
Rated Speed	1710 rpm
Rated Voltage	220V
Frequency	60Hz
Stator Resistance	0.435 Ω
Rotor Resistance	0.816 Ω
L_{ls}	2 mH
L_{lr}	2 mH
L_m	0.0693 mH
Moment of inertia J	0.089 kg-m^2

Voltage Source Converter Specifications
modulation index m_a= 0.8
carrier frequency f_c= 1.05KHz

Reference value of DC Voltage = 600V

CCVSI and Grid specifications

Current margin	0.01A
Grid voltage	100 V
Grid Resistance	0.1Ω
Grid Inductance	0.2H
Grid Frequency	50Hz

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