International Journal of Current Advanced Research
ISSN: O: 2319-6475, ISSN: P: 2319-6505, Impact Factor: 6.614
Available Online at www.journalijcar.org
Volume 7; Issue 5(G); May 2018; Page No. 12716-12721
DOI: http://dx.doi.org/10.24327/ijcar.2018.12721.2245

Research Article

SYNCHRONOUS GENERATOR BASED WIND ENERGY CONVERSION SYSTEM FEEDING ISOLATED LOAD USING VFT

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A R T I C L E I N F O

Article History:

Received 20th February, 2018
Received in revised form 20th March, 2018 Accepted 8th April, 2018
Published online 28th May, 2018

Key words:

Standalone wind energy conversion system, Synchronous generator, Variable frequency transformer, Variable speed wind turbines.

A B S T R A C T

This paper aims to explore the possibility of synchronous generator (SG) based wind energy generation system feeding an isolated load using a power transmission technology i.e. variable frequency transformer (VFT). The configuration proposed in this paper does not employ any power electronics based interface as in conventional SG based stand-alone wind energy conversion systems (SWECS). The simulation models of proposed as well as conventional configuration have been developed using MATLAB for analysis. Further to analyze the effectiveness of the proposed method; the efficiency, total harmonic distortion (THD) of output voltage and THD of output current of the proposed method have been compared with those of the conventional method. From obtained results, it is observed that the proposed method is simple and does not produce harmonics. From the cost analysis, it is observed that the proposed system is cheaper than the conventional system.

INTRODUCTION

Wind power generation capacity in India has increased significantly in recent years. As of 28 February 2018, current census, the total installed wind power capacity was 32.96 GW, which is the fourth largest installed wind power capacity in the world. It is mainly spread across the South, West and North regions. In India, solar power is complementary to wind power as it is generated mostly during the no monsoon period in day time. Due to increasing capacity wind power costs in India are decreasing rapidly. The leveled tariff of wind power reached a record low of 2.43 per kWh during auctions for wind projects in December 2017. Union government made it clear in December 2017 that the valid course of action for tariff-based wind power auctions to bring more simplicity and minimize the risk to the developers. Due to its small installations, stand-alone wind energy conversion systems (SWECS) are quite encouraging in remote area electrification programs. To utilize the wind energy two types of SWECS, fixed speed and variable speed are used. In fixed-speed SWECS, the wind turbines are mostly fitted out with an induction generator because of its simplicity, jaggedness and less maintenance [1-2]. The isolated induction generator is directly connected to the loads. The speed of the turbine is controlled by the gearbox, in order to supply constant voltage and frequency to the load [3].

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The advantages of variable speed wind turbines are more energy capture, operation at maximum power point, improved efficiency and quality of power. Hence, variable-speed wind turbines are the ruling type of turbines as far as present trend is taken into account and used in SWECS for feeding an isolated load [4-5]. Power quality is the main challenge faced in a synchronous generator (SG) based SWECS. This challenge can be overcome by using a current power transmission technology named as variable frequency transformer (VFT) [6].

LITERATURE REVIEW

Power quality is the major problem in synchronous generator based SWECS. With the use of variable frequency transformer (VFT) this problem is reduced to a greater extent. VFT is apprehended using a wound rotor induction machine (WRIM) whose rotor is mechanically coupled to the dc drive motor (DDM) [7]. The SG supplies power to the load at different points of SG input speed. After analysis it is found that the proposed method is cheaper than the conventional method with improved power quality.

Conventional Method

In this method, the wind turbine is connected to the rotor of the SG with or without gear box. Through a power electronics based interface, the output power of the SG is fed to the load. The power electronics based interface comprises of an ac-to-dc rectifier followed by a dc-to-ac inverter as shown in Fig. 1. SG output ac power is first rectified into a dc power using uncontrolled ac-to-dc rectifier [6]. In order to filter out the ripples in the dc power, the capacitor across the output of ac-to-dc rectifier is connected. This dc power is converted again into ac power using self-commutated inverter, which are mainly pulse width modulated (PWM) inverter using insulated gate bipolar transistors (IGBTs). In this type of inverter the reactive power is also controllable. This interface produces harmonic distortion and thus deteriorates the quality of power supplied.

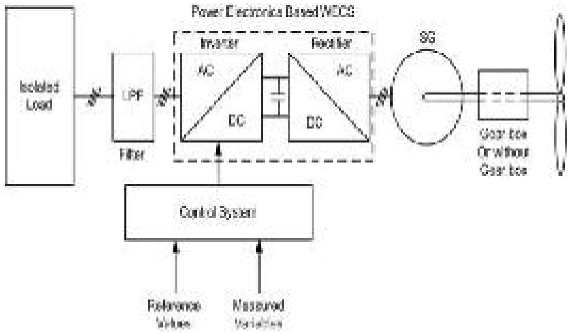

Fig 1 Conventional method

Fig.1 shows that a filter is required at the inverter side in order to meet the standards for harmonic distortion which further increases the cost and complication of the system [8-14].

Proposed Method

This project deals with the analysis of a new configuration of SG based wind energy generation system for feeding power to an isolated load using VFT. The VFT is realized using a wound rotor induction machine (WRIM) whose rotor is mechanically coupled to the dc drive motor (DDM) [20-21]. The SG supplies power to the load at different levels of SG input speed. The requirements of costly power electronics converters are omitted. Hence, the proposed method is simple and does not produce harmonics.

Fig.2 shows the arrangement of VFT. VFT is used to send out electricity between two alternating current frequency domains. Most asynchronous grid inter-ties use high-voltage dc converters, while synchronous grid inter-ties are connected by lines and transformers, but don't have the ability to control power flow between the systems.

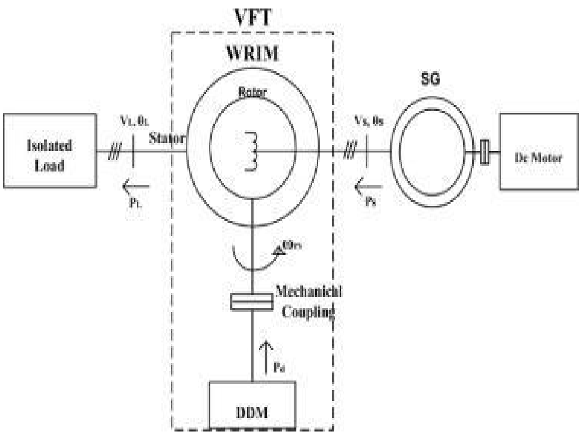

Fig 2 Arrangement of VFT

VFT is used for feeding SG power to load. Here, the wind turbine is connected to the rotor of the SG without a gear box. The stator winding of the SG is connected to the rotor winding of the WRIM. The stator winding of the WRIM is connected to the isolated load [15-19].

Analysis of Proposed Method

We have considered VFT as an ideal machine and neglected magnetizing current and leakage reactance.

Power balance equation will can be written as:

$$P_L = P_S + P_d \quad (1)$$

where;

P_L = electrical power fed to the load,
P_S = electrical power available at output of the SG, and
P_d = mechanical power supplied by the DDM.
We know that the VFT behaves like a transformer, thus, the ampere-turns must balance between stator and rotor windings:

$$N_1 * I_L = N_2 * I_S \quad (2)$$

where;

N_1 = number of turns on stator winding of VFT,
N_2 = number of turns on rotor winding of VFT,
I_L = current fed to load, and
I_S = current supplied by the SG.

Then, both the rotor and stator windings of VFT have the same magnetic flux, so;

$$V_L = N_1 * f_L * Y_a \quad (3)$$

$$V_S = N_2 * f_S * Y_a \quad (4)$$

$$V_S/N_2 = (V_L/N_1) * (f_S / f_L) \quad (5)$$

where;

V_S = voltage of SG on rotor side of VFT,
f_S = frequency of voltage applied across rotor winding of VFT (Hz),
V_L = voltage of load on stator side of VFT and
f_L = frequency of voltage available across stator winding of VFT (Hz), and
Y_a = air-gap flux.

In steady state condition, the rotor mechanical speed in frequency (electrical) is equal to the difference in the frequency (electrical) on the stator and rotor windings of VFT,

$$f_{rm} = f_s - f_L \quad (6)$$

It is known that frequency of rotor is slip times-frequency of stator. Thus, putting fs = sfL in "(6)";

$$f_{rm} = sf_L - f_L = (s-1)\, f_L \quad (7)$$

And

$$N_{rm} = f_{rm} \times 120 / N_p \quad (8)$$

$$\omega_{rm} = 2\pi / 60 \times N_{rm} = 2\pi / 60 \times f_{rm} \times 120 / N_p \quad (9)$$

Where,

s = slip of the VFT,
f_{rm} = VFT rotor mechanical speed in Hz,
N_p = number of poles in the VFT,
N_{rm} = VFT rotor mechanical speed in rpm, and
ω_{rm} = VFT rotor mechanical speed in rad/s.
Combining the above equations gives the power exchanged with the drive system as:

$P_d = P_L - P_S$
$= V_L \times I_L - V_S \times I_S$
$= V_L \times I_L - [(N_2 \times (V_L / N_1) \times (f_S / f_L)) \times (N_1 \times (I_L / N_2))]$
$= V_L \times I_L - [(sV_L) \times I_L]$
$= V_L \times I_L \times (1-s)$ or, $P_d = P_L \times (1-s)$ (10)

It shows that the electrical power flowing into the load is dependent on the mechanical power of the DDM and slip of WRIM.

If P_L is constant, then

$P_d \propto (1-s)$ and $s = f_S / f_L$

Since load frequency is maintained constant, then;

$s \propto f_S$ and $f_S \propto N_S$
Hence,
$s = kN_S$
where,
k = constant,
N_S = SG speed.

Thus,
$P_d \propto (1 - kN_s)$ (11)
For constant load, the mechanical power of the DDM decreases with increase in the SG speed.

If the slip of WRIM is maintained constant, then

$P_d \propto P_L$ (12)
At a constant slip, the electrical power fed to the load is being only proportional to mechanical power of the DDM.

Matlab Analysis of Conventional Method

Matlab Simulink Model

SG is simulated with the synchronous machine pu standard. Ratings are 3 phase, 8.1 kVA, 1500 rpm, 400 V, 50 Hz and the load is simulated using three-phase series R load as shown in Figure 3. SG is connected to rectifier side of the power electronics based interface and load is connected to inverter side.

In this, rectifier is simulated with the universal diode bridge and the inverter is simulated with universal IGBT Bridge using PWM technique. A constant block named as dc motor is used to apply rated speed at input of the SG.

The voltage and frequency of different loads are kept constant i.e. 400 V (L–L) and 50 Hz.

The resultant model is shown on the figure below.

RESULTS

Table 1 depicts the power fed to different loads at rated value of input SG speed. It is obvious from this table that efficiency of the conventional system increases with the increase in value of load (at 1 kW load the efficiency is 91.31%), reaches to maximum value (93.80%) at 2 kW load and then starts reducing with further rise in load value.

Table 1 Power fed to different loads at 1500 rpm

S. No.	Ps (W)	PL (W)	% η = (PL/Ps) ×100
1.	1095	1000	90.23
2.	2148	2000	92.11
3.	3246	3000	91.42
4.	4395	4000	90.01

Matlab Analysis of Proposed Method

Matlab Simulink model

VFT is simulated with an asynchronous machine which is a doubly-fed, 3 phase, 7.5 kW, 400 V, 50 Hz, 1440 rpm WRIM and the isolated load is simulated with three-phase R load having rated voltage 400 V at rated frequency of 50 Hz

The three-phase R load is connected to the stator of WRIM and SG (3 phase, 8.1 kVA, 1500 rpm, 400 V, 50 Hz) is connected to rotor windings of WRIM.

A block named as dc motor is used to supply various speed at the input. DDM is simulated with separately excited dc motor. The output mechanical power of the DDM is applied to the rotor of WRIM is of mechanical torque 'Tm'. The voltage and frequency of the load is kept constant and the input speed of the SG is varied.

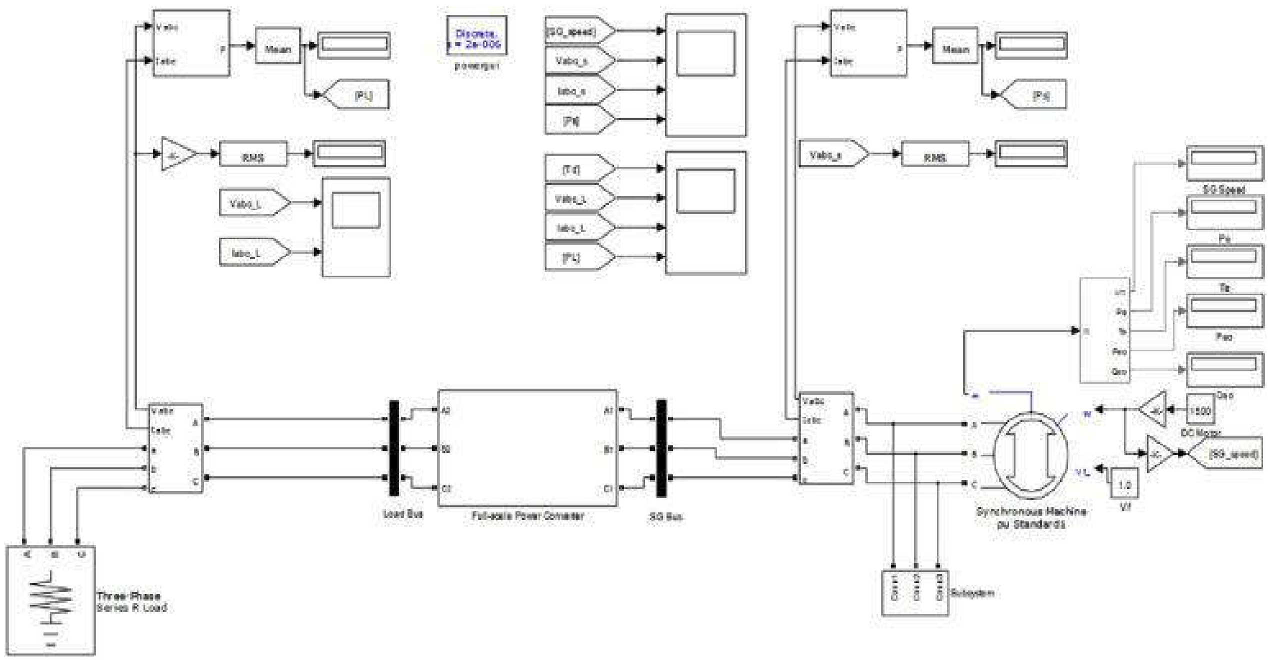

Figure 3 Simulink model of conventional method

The three-phase capacitor branch is connected across the stator windings of the WRIM to supply reactive power required at stator side of the WRIM.

The simulated model is shown below:

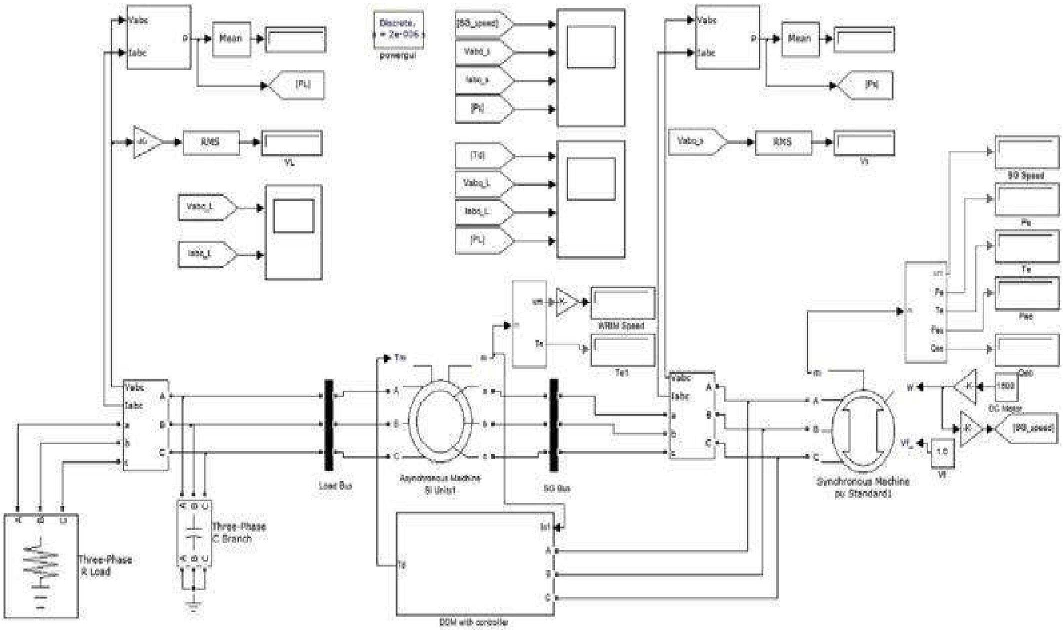

Figure 4 Simulink model of proposed method

RESULTS

For constant load

1 kW, 2 kW, 3 kW and 4 kW loads are supplied at different values of SG input speeds. As we know that the load frequency is dependent upon slip of the VFT, mechanical power from DDM is varied which controls the speed of WRIM and hence the slip of the VFT. So, by controlling the slip, the load frequency is maintained constant at 50 Hz consequently.

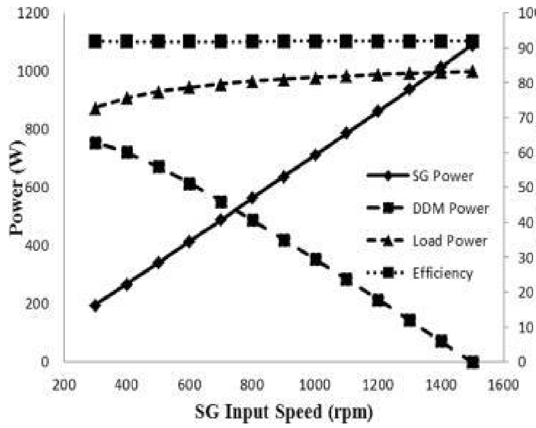

Figure 5 Speed vs Power curve

For 1kW load

SG is operated at different speeds for feeding a 1 kW load. DDM power is varied by DDM controller which varies the torque applied at the rotor of the WRIM, thus controlling the slip of the machine in order to supply power to the load at 50 Hz. Results are shown in “Table 2”.

When SG is operating at rated speed i.e. 1500 rpm, the voltage available across the stator terminals of the SG is 394 V which is near to rated voltage (400 V) and its frequency is 50 Hz (rated frequency). The output power of the SG is 1089 W.

Comparison of Proposed Method with Conventional Method At 1500 rpm

From Table 3 it is clear that in conventional SWECS, the THDs of inverter output voltage and current without filter are very high and violate permissible limits. Hence, filter is required in order to bring these THD's within permissible limits. After filter both THD's comes within permissible limits. Whereas, in proposed SWECS, the THDs of VFT output voltage and current are very less than the conventional system and are within permissible limits. Thus, here no filter is required. Further, the efficiency of both conventional and proposed methods increases with the increase in load from 1 kW, gets a maximum value at 2 kW and then starts decreasing with the further increase in load. Moreover, the efficiency of proposed method is slightly greater than the conventional system which is around 0.5%.

Table 2 Variation in output at various input speeds at 1 kW load

N_s(rpm)	V_s(V)	f_s(Hz)	P_s(W)	P_d (W)	N_{rm}(rpm)	S = [(1500−Nrm)/1500]	V_L(V)	P_L(W)	% THD of V_L	% THD of I_L	% η = [PL/(Ps+Pd)]×100
1500	394	50	1090	0.025	0	1	400	1000	0.01	0.01	91.83
1400	362.7	46.67	1010	72.01	100	0.93	399.4	996.4	0.01	0.01	91.83
1300	339.8	43.33	948.32	143.44	200	0.87	398.5	992.5	0.01	0.01	91.85
1200	315.7	39	860.21	214.23	300	0.80	397.6	988.2	0.01	0.01	91.84
1100	290.4	36.24	786.7	284.25	400	0.73	396.8	983.5	0.01	0.01	91.83
1000	260.5	32.45	710.11	353.79	500	0.67	395.5	978.2	0.01	0.01	91.8

Hence from Table 3, it is concluded that the proposed method is having slightly greater efficiency with almost negligible THD.

Cost analysis

The cost analysis of both the methods have been done and the data has been taken from the Ref. [22].

Table 3 Comparison of proposed and conventional method

Conventional method					Proposed method		
% THD of VL without filter	% THD ofIL without filter	% THD of VL with filter	% THD of IL with filter	% η	% THD of VL	% THD of IL	% η
67.93	17.48	3.96	3.96	91.3	0.01	0.01	91.83
68.15	16.37	2.75	2.75	93.11	0.01	0.01	93.63
67.96	17.76	2.91	2.71	92.42	0.01	0.01	93.05
68.06	16.68	2.72	2.69	91.01	0.01	0.01	91.07

Table 4 Cost analysis

Equipment	**Direct-drive SG**				
Conventional		Proposed			
		SG	WRIM	DDM	TOTAL
Iron (kg)	32.5	32.5	4.03	1.34	37.87
Copper (kg)	12.6	12.6	1.21	0.40	14.21
Total (kg)	45.1	45.1		52.08	
SG active material cost	287	287		287	
SG construction cost (Euro)	160			160	
WRIM active material cost (Euro)	-			30	
DDM active material cost (Euro)	-			10	
(WRIM+DDM) construction cost (Euro)	-			40	
Converter cost (Euro)	120			-	
Total cost (Euro)	**567**			**527**	

Table 4 shows that proposed method is cheaper than conventional method.

CONCLUSION

From the simulation results, it is evident that with decreases in SG input speed, the SG output power decreases but the DDM power increases in order to supply power to the load at constant frequency and voltage. Even though with the increase in DDM power, the load power reduces slightly but the efficiency is maintained constant. Then the power fed to variable load by the SG based SWECS at fixed speed i.e. 1200 rpm without and with excitation control has been analyzed using simulation model of proposed method. From here it is concluded that the power fed to load increases linearly with the DDM power. The load power as well as efficiency with excitation control are slightly higher than without excitation control. Both increases with the increase in load, reaches to the extreme value and then starts reducing with the further increase in load. Besides, the THD of output voltage, THD of output current and efficiency of the proposed method have been compared with those of the conventional method. From the comparison results, it is found that the proposed system does not produce harmonics and having slightly higher efficiency than the conventional system.

Further, cost analysis has also been carried out for the proposed system and it has been compared with that of conventional system. From the cost analysis, it is observed that the proposed system is cheaper than conventional system.

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How to cite this article:

Surendra Kumar Tripathi *et al*(2018) 'Synchronous Generator Based Wind Energy Conversion System Feeding Isolated Load Using Vft', *International Journal of Current Advanced Research,* 07(5), pp. 12716-12721.
DOI: http://dx.doi.org/10.24327/ijcar.2018.12721.2245

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