APPLICATION OF VARIABLE FREQUENCY TRANSFORMER (VFT) FOR INTEGRATION OF WIND ENERGY SYSTEM

A THESIS

*Submitted in partial fulfilment of the
requirements for the award of the degree*

of

DOCTOR OF PHILOSOPHY

in

ALTERNATE HYDRO ENERGY CENTRE

by

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JANUARY, 2017**

ABSTRACT

Among various renewable energy resources, wind has been proven to be the most promising resource over the past few decades due its environment friendliness and sufficient potential to overcome the problems of energy shortage. The wind turbine generators (WTGs) employed for converting the wind energy into electrical energy are operated either at fixed-speed or at variable-speed mode. Among these two modes, the variable-speed mode is mostly preferred nowadays, as the torque can be held almost constant over a wide range of power by varying the speed. This alleviates the stresses imposed on the structural components and thus, the wind turbine can be made lighter and cheaper. Further, variable-speed WTGs have many advantages over fixed-speed WTG such as increased energy capture, operation at maximum power point, improved efficiency and power quality.

A conventional variable-speed wind energy conversion system (WECS) consists of a wind turbine, gearbox, WTG and power electronic interface system. The power electronic interfacing is employed for integration of WECSs with grid or to supply isolated load, which is costly, incorporates sophisticated control, causes harmonic distortion and thereby deteriorates the quality of power supplied to grid or load. Therefore, suitable compensation is required in order to meet the standards for harmonic pollution which further increases the cost and complexity of the system. The average failure rate of power electronic conversion system is highest among other components of WECS. Further as, the wind speed does not remain constant, hence the repeated switching ON and OFF of WECS becomes very common which ultimately causes stress on the grid and may lead to stability related issues in the grid.

Keeping in view the aforesaid problems of conventional method used for integration of WECS, the present study was planned with the following objectives:

i) To identify a new integration technology for WECS which can address the above challenges and at the same time, provide effective utilization of wind power at small as well as large scales.

ii) To study and investigate the concept and operation of the identified technology in detail.

iii) To simulate the identified technology for integration of WECS.

iv) To compare the proposed integration method for WECS with conventional method in terms of performance and cost.

v) To develop an experimental setup of proposed integration method for WECS so as to validate the simulation results.

vi) To perform steady state analysis of proposed integration method.

In order to fulfill the above mentioned objectives, a new power transmission technology named as variable frequency transformer (VFT) is identified as a flexible AC link for connecting WTGs to the grid or load. VFT is basically a rotary transformer which transfers the electrical power in-between power system networks. The power flow through VFT can be regulated in terms of both magnitude and direction by controlling the torque of DC drive motor (DDM) coupled with the rotor of VFT.

For analyzing the operation of VFT, its simulation model has been developed under MATLAB Simulink environment for power transfer in-between synchronous and in-between asynchronous grids. In this work, VFT is modeled as a doubly-fed wound rotor induction machine (WRIM) whose rotor is mechanically coupled to DDM. Among the two grids (#1 and #2), the grid #1 is connected to the stator side of VFT while grid #2 is connected to the rotor side of VFT. A DDM is used to apply torque to the rotor of VFT so as to regulate the power flow in-between these grids. From the simulation results, it is found that the magnitude and direction of power flow in-between the grids are controllable and directly proportional to the torque applied by DDM.

In order to validate the simulation study, the experimental work has also been carried out. The trends of power flow in-between synchronous and asynchronous grids achieved from the experimental results are similar to that achieved from the simulation results. Thus, the concept and application of VFT as discussed in literature are verified by simulation and experimental studies. Further, a simulation model of controller has also been developed for closed loop control of power flow through VFT. Conducting simulation studies in presence of this controller, it is concluded that both the magnitude and direction of the power transfer in-between the synchronous and asynchronous grids are controllable by the controller.

Further, for fault analysis of VFT during synchronous power transfer, three-phase fault has been simulated at two different locations (stator and rotor sides) of VFT (one at a time). From the obtained simulation results, it is concluded that when three-phase fault

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occurs at either side of VFT, it works as an induction motor and instead of transmitting power it takes power from the healthy side. Moreover during fault, VFT doesn't contribute the fault current.

After verifying the application of VFT for power transfer in-between synchronous and asynchronous grids, its application has been explored for grid integration of permanent magnet synchronous generator (PMSG) based WECS. The simulation model of the proposed method has been developed in MATLAB Simulink. From simulation results, it is observed that the power flow from PMSG to grid is proportional to the magnitude of applied torque to the rotor of VFT. The efficiency of power transfer through VFT also increases with the applied DDM torque, achieves a maximum value and then starts decreasing with the increase in magnitude of applied torque to its rotor. Further, a simulation model of controller has been developed which maintains the power flow from PMSG to grid at maximum efficiency point. The performance of modeled controller has been checked at different values of PMSG speed and found to be satisfactory.

In order to compare the proposed method used for integration of WECS with conventional method, a digital simulation model of the conventional WECS has also been developed in MATLAB Simulink. From the comparison, it is observed that the proposed system is having almost similar efficiency but produces negligible harmonics as compared to the conventional system. Moreover, harmonics produced by the proposed system are within permissible limits thus the requirement of filter is omitted. Further, weight and cost of proposed system have been compared with the conventional system, which indicates that the proposed system is cheaper than conventional system but heavier in weight.

After realizing the above concept on PMSG based WECS, a similar concept is extended for grid integration of wound rotor synchronous generator (SG) based WEGS. For this purpose, a digital simulation model of VFT for grid integration of SG based WEGS has been developed using MATLAB Simulink. The power flow from SG to grid under different torque conditions is analyzed using the developed model. From the simulated results, it is found that the active power flow from SG to grid is directly proportional to DDM torque. Also by controlling the applied DDM torque, VFT can be operated at its maximum efficiency. Further, a simulation model of controller has been developed which maintains the power flow from SG to grid at maximum efficiency point.

The performance of modeled controller has been analyzed at different values of SG speed and found to be satisfactory.

In order to check the suitability of the proposed system, the performance of the proposed system at different values of SG speed have been compared with those by the conventional method in terms of total harmonic distortion (THD), efficiency, weight and cost. From comparison, it is observed that the efficiency of proposed system is almost similar to that of conventional system. However, the quality of voltage and current supplied to grid by the proposed system is much better in comparison to that of conventional system. Further, the comparison of weight (iron and copper) and cost required by proposed and conventional systems shows that proposed system requires more iron and copper than conventional system but cost of proposed system is less than conventional system. For validating the obtained results by simulation of proposed system, its experimental analysis has also been carried out. The trends of power flow from SG to grid and efficiency of the system achieved from the experimental work validate the simulation results.

In the present energy scenario, due to high cost and complexity associated with the grid extension in remote and rural areas, small scale power generation has received greater attention to serve the local loads. Therefore, the application of VFT has been extended to feed isolated loads from WECS. For this purpose, a simulation model of VFT for integration of SG based WECS with isolated load has been developed under MATLAB Simulink environment with and without excitation control of SG. The simulation results show that with increase in SG speed, the difference between frequencies of input and output voltages of VFT decreases, thus DDM power required to maintain constant frequency at load end also decreases. Moreover, due to excitation control of SG, the load voltage is maintained constant at its rated value and hence constant load power is achieved. Thus, the proposed method is able to effectively utilize the small amount of power available at the output of SG and hence avoids the wastage of power due to the low value of wind turbine speed.

Further, two controllers i.e. slip controller and excitation controller have been simulated for closed loop control of proposed scheme supplying an isolated load from SG based WECS. The use of both controllers in the simulation study shows that the modeled controllers are able to maintain the load voltage as well as its frequency constant at their rated values. Moreover, a comparison has been made between proposed and conventional

systems in terms of THD, efficiency, weight and cost. The comparison shows that the proposed system is cheaper, doesn't produce harmonics and having almost similar efficiency but heavier in weight than the conventional system.

In order to validate the simulation study, the experimental work has also been carried out for the proposed system feeding an isolated load without excitation control of SG. From experimental results, it is found that with decreases in SG input speed, the SG output power decreases but DDM power increases in order to supply power to the constant load. The power fed to load increases linearly with DDM power. Moreover, by controlling the slip of VFT, the output frequency of voltage fed to the load is maintained constant at its rated value. On comparing the experimental results with simulation results, it is concluded that both the results are following similar trends.

Finally, the steady state analysis of the proposed system used for feeding an isolated load is also carried out. For steady state analysis, first steady state equivalent circuit of VFT has been derived. Then, the developed equivalent circuit of VFT has been used for preparing the model of its application in standalone WECS. A set of equations has been derived from the model of proposed VFT application. Then a numerical based routine 'fsolve' in the MATLAB is used for solving the set of equations. For validation of equivalent circuit of VFT, the experimental work has also been performed. The comparison shows that both results are in close agreement. After this, the analysis has been further extended for variable load under different values of SG speed and load power factor. As load power increases, the SG output power, DDM mechanical power, SG current and load current also increase. For a given load, as SG speed increases, DDM power decreases. For a lagging power factor load, SG has to generate more power and thus supplies more current than for unity or leading power factor load.

The work presented in the thesis can be summarized as:
➤ The application of VFT has been analyzed for power transfer in-between synchronous and in-between asynchronous grids by simulation and experimental studies. Further, a controller has been simulated for achieving closed loop control of power flow through VFT. The developed simulation model is also used for analysis of VFT during three-phase fault.
➤ The application of VFT for grid integration of PMSG based WEGS is analyzed and compared with the conventional method in terms of performance, weight and cost by simulation studies. Further, a simulation model of controller has been

developed which maintains the power flow from PMSG to grid at maximum efficiency point under different values of PMSG speed.

- The application of VFT for grid integration of wound rotor SG based WECS is analyzed by simulation and validated by the experimental work. A simulation model of controller has also been developed to operate the proposed system at maximum efficiency point under different values of SG speed. The proposed method for integration of WECS is also compared with the conventional method in terms of THD, efficiency, weight and cost.

- The application of VFT is extended for feeding an isolated load from wound rotor SG based WECS by simulation study. The experimental work is also carried out to validate the simulation results obtained without excitation control. Moreover, two controllers i.e. slip controller and excitation controller have been simulated for closed loop control of the proposed scheme. The performance, weight and cost of proposed method are also compared with that of conventional method for feeding an isolated load.

- The steady state analysis of VFT for feeding an isolated load from SG based WECS is carried out by deriving a set of equations from its model and then solving these equations using an iterative technique. For validation, the solutions obtained are compared with the experimental results. After this, the steady state analysis of VFT has been extended for variable load under different values of SG speed and load power factor.