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It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.


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I, **Prateek Utkarsha**, certify that the work embodied in this thesis is my own bonafide work and has been carried out by us under the supervision of **Dr. N. K. Swami Naidu** from July-2018 to July-2024, at the Departement of Electrical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi (UP). The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, thesis, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 24.12.2024

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**Signature of the student**

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It is certified that the above statement made by the student is correct to the best of our knowledge.

**Dr. N.K. Swami Naidu**

**(Supervisor)**

**Signature of Head of Department**

**Prof. R. K. Singh**

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**To**

**My Parents**

**My Elder Brother**

**My Wife Bhavya**

**and**

**My Friends**

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Date: ____________________ Prateek Utkarsha

# Abstract

Integration of renewable energy sources (RES) into the power system has increased to reduce carbon emissions through sustainable energy generation. Power system is slowly transitioning from centralized power generation with synchronous generators (SGs) to RESs based distributed generation. RESs such as solar, wind etc. are intermittent in nature which is a major problem associated with it. But, synchronous generators have large inertia due to the rotating mass, which plays an important role in the events of disturbance, to balance the generation and load demand. Kinetic energy is stored in the rotor of the SG and it is proportional to the inertia associated with it. When any disturbance occurs in the power grid, rotor releases or absorbs the kinetic energy to match the generation and demand.

However, the RESs consists of power electronic converters such as DC-DC converter, voltage source inverters etc., don't have inertia due to the absence of any rotating parts. Hence, the high penetration of RESs has reduced the overall inertia of the power system. Inertia plays a vital role in maintaining the frequency stability of power systems. Lower inertia increases the frequency deviation and rate of change of frequency (RoCoF) in the events of disturbances. High RoCoF can cause the pole slipping of generators, false tripping of circuit breakers etc. So, low inertia results in the frequency instability of the RESs based power system. Also, in some cases, anti-islanding protection is designed based on the RoCoF detection. Hence, RoCoF must be within specified limits. To overcome these problems, high inertia is required in the RESs based power system.

To emulate the inertia numerous methods have been introduced in the literature such as dc-link capacitors, supercapacitors, batteries etc. Recently, virtual synchronous generator (VSG) has been introduced for the inertia emulation. Different names of VSG has been used in the literaure such as virtual synchronous machine (VSM), synchronverter etc. The idea behind all these methods is to control an inverter to emulate an actual

synchronous generator operating in the power grid. A hardware setup of a grid-connected VSG is developed in the laboratory. Synchronization is very crucial in case of a VSG for grid integration. Phase-locked loop (PLL) is generally used for the grid integration of VSG. Recently, many self-synchronizing methods have been introduced in the literature. In this work, a self-synchronization control algorithm has been used for the grid integration of VSG.

A seamless transfer of virtual synchronous generator using virtual synchronizing torque controller is presented for smooth integration with the distribution grid. The controller provided the necessary synchronizing torque to keep the frequency and angle mismatch between the utility voltage and the VSG voltage to a minimum. Virtual synchronizing voltage has reduced voltage amplitude error. Therefore, without employing any phase-locked loops, the performance of the VSG synchronization is improved. Furthermore, the proposed controller eliminates the proportional-integral (PI) regulators from the power controller of VSG, which requires accurate parameter tuning, like PLL gains. Also, control modifications are not required during standalone or grid-connected modes. The proposed method requires no additional controller to identify the unwanted islanding situations because the operating mode can be deduced from the synchronizing torque value. Also, the proposed synchronizing controller is compared with the three different synchronization methods, i.e., PLL-based VSG, synchronverter and presynchronization control and observed that the proposed synchronization method is faster than the other three methods and shows less overshoot in VSG frequency.

The virtual inertia and damping of traditional VSG explained above are fixed. Active power and frequency of the VSG oscillates more in the events of large disturbance. Since, the inertia and damping are constant they can't be changed for the different kinds of transients. Hence, there is a need to adaptively change the inertia and damping for different kind of disturbances. Hence, an adaptive control strategy with flexible virtual inertia and damping coefficient is proposed for optimizing the energy storage unit during grid frequency variations. The proposed control method is verified in the developed experimental prototype. In addition, proposed control algorithm is compared with the currently available adaptive control approaches like adaptive inertia control (adaptive $J$ control) and alternating inertia and damping (alternating $J$ and $D_P$ control) based VSG and observed that the energy storage requirement and the oscillations in the active power and frequency are minimum in the proposed control method as compared to the other two methods.

VSG have many applications such as grid-connected photovoltaic systems, wind energy systems etc. VSG control algorithm in a grid-connected PV system is implemented in this thesis. A single-stage self-synchronized PV-VSG with a seamless mode control (SMC) algorithm is presented to provide ancillary support to the grid frequency disturbances by maintaining power reserve and also working as a STATCOM during the unavailability of PV power. It eliminates the requirement for the storage element to provide frequency support. The proposed PV-VSG works in self-synchronizing mode. Hence, there is no need for PLL for the grid synchronization. It can supply the non-linear loads without using any additional harmonics compensation methods.The proposed PV-VSG is able to shift seamlessly from grid-tied mode to islanded mode in the event of grid faults during the day. During the nighttime, PV-VSG works as a STATCOM to support the reactive power demands. No separate control algorithm is required for the STATCOM operation to maintain DC link voltage. The performance of the proposed SMC controller under various cases is presented through experimental results.

Another application of VSG is unified power quality conditioner. With the VSG inverter, one more series converter is added at the dc link to mitigate the voltage power quality problems such as voltage sag, swell, grid voltage harmonics etc. This arrangement will look like a UPQC. So, a multifunctional unified power quality conditioner (MUPQC) for DG application to emulate the behaviour of a synchronous generator has been presented in this thesis. The synchronous machine characteristics are integrated into the shunt converter control algorithm, so that this MUPQC can add virtual inertia to the grid to regulate the frequency. Implementation of the virtual synchronous machine in MUPQC provides a reliable and simpler control method and completely removes the synchronizing element like PLL. In addition, the proposed MUPQC synchronverter control is capable of working in standalone as well as grid-tied mode. This feature of the proposed MUPQC makes it a viable choice for the micro grid applications. The proposed MUPQC is implemented in MATLAB/Simulink platform and validated for voltage sag, swell, harmonics compensation for load current and frequency disturbance conditions. The proposed MUPQC is very much suitable to work in future grid connected systems comprising large number of power electronics devices.

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# List of Abbreviations

| | |
|---|---|
| **AC** | Alternating current |
| **APL** | Active power loop |
| **AT** | Auto-tuned |
| **BESS** | Battery energy storage system |
| **COP26** | Conference of parties |
| **DVR** | Dynamic voltage restorer |
| **DLFR** | Double line frequency ripple |
| **DC** | Direct current |
| **DG** | Distributed generation |
| **DES** | Distributed energy sources |
| **DSP** | Digital signal processing |
| **GFL** | Grid following inverter |
| **GFM** | Grid forming inverter |
| **FLL** | frequency-locked-loop |
| **HVDC** | High voltage direct current |
| **IGBT** | Insulated gate bipolar transistor |
| **MUPQC** | Multi functional unified power quality conditioner |
| **MPPT** | Maximum power point tracking |
| **MOSFET** | Metal oxide semiconductor field effect transistor |
| **PWM** | Pulse width modulation |
| **PV** | Photovoltaic |

| | |
|---|---|
| **PV-VSG** | Photovoltaic Virtual synchronous generator |
| **PLL** | Phase-locked-loop |
| **PI** | Proportional-integral |
| **PQ** | Power quality |
| **PWM** | Pulse-width modulation |
| **PCC** | Point of common coupling |
| **RoCoF** | Rate of change of frequency |
| **RPL** | Reactive power loop |
| **RES** | Renewable energy sources |
| **SG** | Synchronous generator |
| **STATCOM** | Static compensator |
| **SMC** | Seamless mode control |
| **THD** | Total harmonic distortion |
| **UPQC** | Unified power quality conditioner |
| **VSI** | Voltage source inverter |
| **VSG** | Virtual synchronous generator |
| **VSM** | Virtual synchronous machine |