Recent Trends on Integration and Control of Renewable Energy Systems for Rural Electrification

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Abstract: At present times many countries including India are shifting from conventional energy resources to renewable energy resources. Renewable energy resources are associated with advantages like zero carbon emissions and their suitability to act as autonomous power plants. The biggest problem with renewable energy-based system is their control strategy when used as autonomous power plants or in integration with the grids. Main renewable energy sources like solar and wind are highly intermittent in nature as both solar irradiance and wind speeds change from time to time, which changes the power quality characteristics like voltage magnitudes, frequency level, active and reactive power flows. In order to prevent these parameters from changing their levels beyond specified limits well designed control strategy is the need of hour. This paper highlights the various available control techniques, power electronic circuitry and brings out observations and findings that can be implemented for the flexible, effective and efficient control in renewable energy-based power plants.

Keywords: Integrated System, Distribution System, Control, Homer, Energy Storage, Compensation

I. INTRODUCTION

In modern world the rural and some industries are electrified by hybrid and integrated renewable energy systems. However, for proper control of these systems there are some key communication and measurement technologies like smart meters, Phase measurement units (PMU), advanced metering infrastructure (AMI), Google mapping tools and multi agent technology. These technologies can be implemented to get real time information about the various states of the system which can help the controllers to generate correct control actions in micro and integrated systems.

Renewable energy-based systems are intermittent in nature, there power output parameters like voltage, frequency, load angle, active and reactive power flows over the network keeps on changing as the input parameters like solar irradiance, wind speeds of system change. For maintaining different parameters within specified and safe limits, different control and estimation techniques are used. For maintaining voltage levels at various nodes different controllers are used like automatic voltage regulators, dynamic voltage regulators and reactive power-based compensation technique. Apart from these direct control strategies some indirect techniques like energy storage-based control, non-linear load control, probabilistic techniques for distribution generation control, adaptive and predictive control strategy can be implemented in hybrid and integrated renewable energy systems. These all control techniques will help in supplying the quality power to the consumers [1].

II. INTEGRATED SYSTEM SIMULATION MODELS

Canales et al. [2] carried a case study to compare wind hydro hybrid system having conventional hydro plants with reservoir (HWR) with wind hydro hybrid system having hydropower plants with pumped storage capabilities (PSH). The software used for this comparison was Homer. The real data related to Rio Grande do Sol, which is a state of south Brazil, was used. It was found that the Hybrid System with (PSH) reduces

cost, increases the installed capacity and increases the environmental benefits.

Martin and Davis [3] studied the integration of wind, solar & biomass for a year. They proposed a model through which we could produce constant methane by utilizing the wind& solar power for carrying out the electrolysis process for hydrogen production & by utilizing biomass energy for gasification process for methane generation as explained in Figure 1 It was also found that the best optimal technology used for biomass processing was, using Ferco indirect gasifiers, which reduces the overall cost of the installation of integrated systems having biomass as its one constituent.

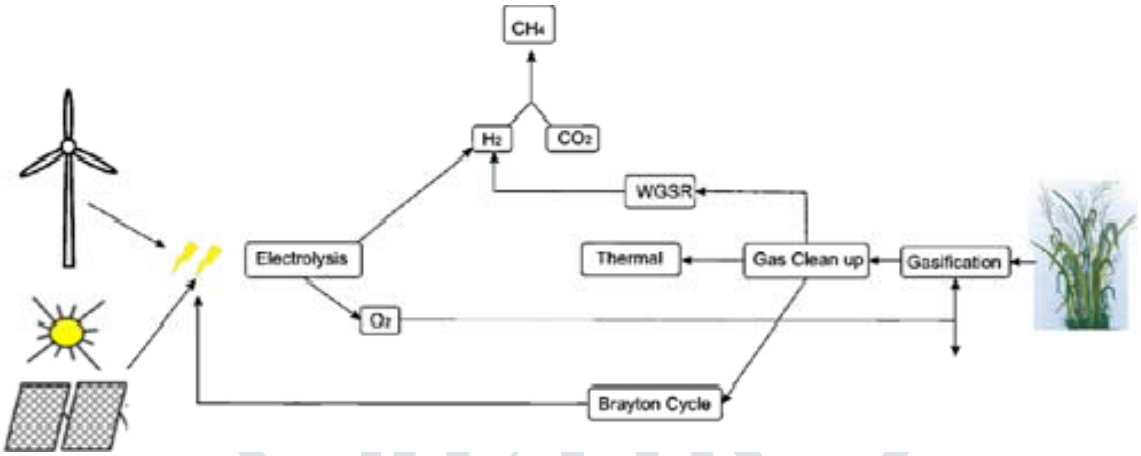


Figure 1: Renewable resources integration for constant production of methane

Montuori et al. [4] studied how demand response led to the better integration of renewable resources like wind, solar, hydro, & biomass. The tool they used was Homer software. This software provides optimal & economic combination of renewable resources. The standalone system configuration was consisting of primary consumer, generators supplied by diesel, natural gas, synthetic gas obtained from gasified biomass. It was found that when generation from gasified biomass decreased, the NPC (Net Present Cost) for various configurations goes up & vice versa if decreased.

Lopez and Espiritu [5] Studied how hybrid systems can be evaluated. Renewable energy power penetration& energy storage scheme are main parameters for system evaluation. They used homer software for hybrid system simulation. The results obtained from single objective software homer were used to get optimal & best solution by using pareto- front idea for multi-objectivity conditions for dominant solutions are given below:

1. x_1 is no worse than x_2 in all objectives; i.e., $f(x_1) \leq f(x_2)$ for all I, I = {1, 2… n}.
2. x_1 is strictly better than x_2 for at least one objective; i.e., $f(x_1) < f(x_2)$ for at least one I.

Fang et al. [6], made a survey on literature on smart grids till 2011. They discussed the enabling technologies in smart grids like smart information system, smart management system, improved efficiency technologies, cost reduction technologies & smart protection. They made a comparison between an existing grid & a smart grid. Table 1 brings the comparison between the two. They concluded that smart grids with enabling technologies provide reliable electricity with increased storage capacity, reduction in greenhouse gases emission & improved maintaining system. The wireless & PLC played role for two-way communication.

TABLE 1: A Brief Comparison between the Existing Grid and the Smart Grid

Existing Grid	Smart Grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-Monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and

	islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

Elamari et al. [7] studied the power balancing & frequency problems in systems associated with renewable energy resources. The problems associated with renewable energy resources are that of fluctuations & intermittent. The methodology used for power balancing & frequency control was using electric water-heater. The model was implemented in Matlab to get observation regarding power consumed & temperature rise. It was concluded that this strategy is better than using energy storage methods as it was cost effective & power & frequency balancing was achieved on demand-side.

Wollny et al. [8] studied AC coupled mini- grids & hybrid systems. The various sustainable energy resources like solar, wind, biomass, hydro & wave play crucial role for future energy. However, their integration for reliable electricity is very important. The methodology of AC coupling in hybrid & mini-grids has increased reliability & reduced cost. The bi-directional inverter plays its crucial role for control purposes in AC coupled circuits. More the methods of frequency control, voltage control remains same as that of conventional power systems. It was concluded AC coupling has revolutionized smart grids.

Divan et al. [9] studied the power flow controlling devices over transmission lines. Since the problem associated with the use of FACT devices was of high cost & reliability problems. Here the methodology used for power control was by using DSSC (Distributed Static Series Compensator). It changes the impedance of lines & hence controls the active power flow over the lines. Figure 2 shows DSSC circuit schematic. It was concluded that by using DSSC power flow control technique, it is cost effective & highly reliable for both high & extra high voltage lines.

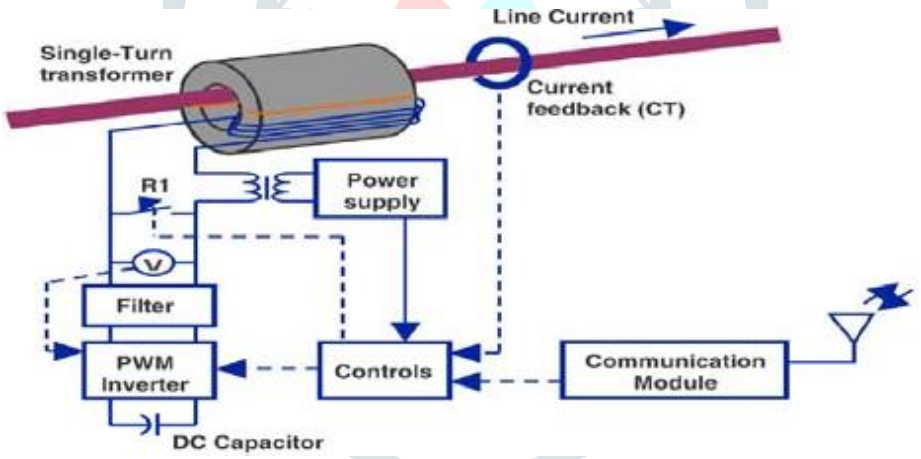


Figure 2: DSSC circuit schematic.

Bhandari et al. [10] proposed hybrid systems for two remote locations- Lama Hotel in Rasuwa district & Thingan in Makawanpur district of Nepal. The methodology used for developing hybrid system consists of solar photovoltaic (PV), wind & hydro was hybrid charge controller (HCC) & grid-tie- inverter (GTI). It was concluded that hybrid systems connected to mini-grids increases reliability & satisfies demand for the remote villages or for mountainous regions.

Heydari and deh [11] studied the hybrid systems consisting of photo voltaic & biomass energy systems for providing electricity to wells for agricultural purposes. They used TNPC (total net present cost) for economic analysis & also performed optimization of solar photovoltaic area & size of biomass generator. The methodology used for simulation & optimization process was heuristic technology (harmonic search), where Matlab software was used. It was concluded that photovoltaic system together with biomass generator provided reliable & cost-effective electricity than photovoltaic alone.

Yamegueu and Azoumah [12] studied solar photovoltaic & diesel hybrid system for kamboise located in Barkino Faso. During their study, they considered the simulation model of hybrid system (PV/diesel) without any storage element present as shown in Figure 3 The load considered was a constant one. At various load levels small, medium & large, it was concluded that the most suitable load level for efficient operation

of PV/diesel hybrid system is at high load. Further this analysis is open for variable load case & research is going on it.

Yap and Kari [13] studied the off-grid hybrid PV/diesel system. For remote areas grid connectivity is not feasible. So it is better to go for diesel based systems, however, due to addition of photovoltaic system, the dependency on diesel based system decreases & overall reliability increases. The methodology used for studying hybrid system (PV/diesel) was that of development of model. The modeling was done by dynamic modeling (simulink) & artificial neural networks (ANN).

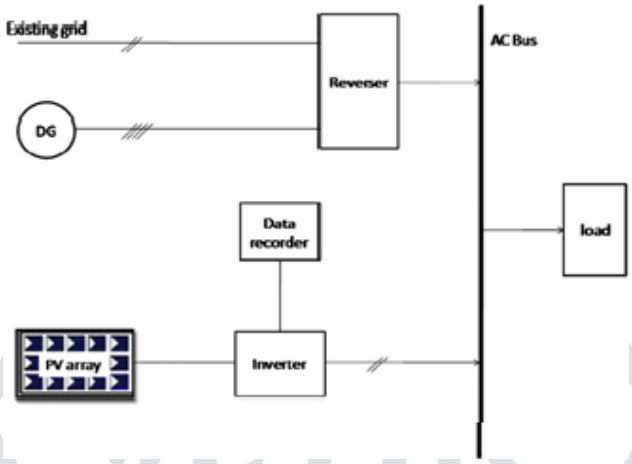


Figure 3: Hybrid system consisting of diesel and PV system without storage element

The experimental data was used for training ANN. Figure 4 shows the main Simulink model, which is capable of predicting solar radiations & representing power flows in the system. It was concluded that proposed model is better planning & analyzing model for off-grid PV/diesel based system than existing tools & also thin model is expandable one.

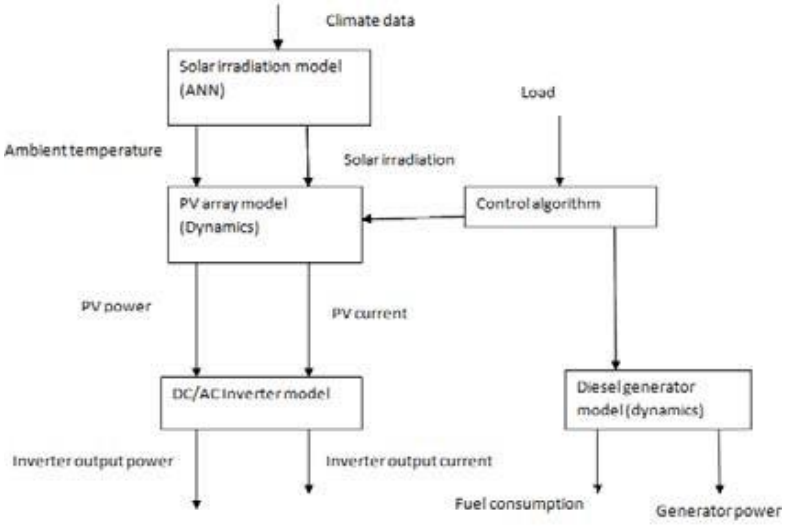


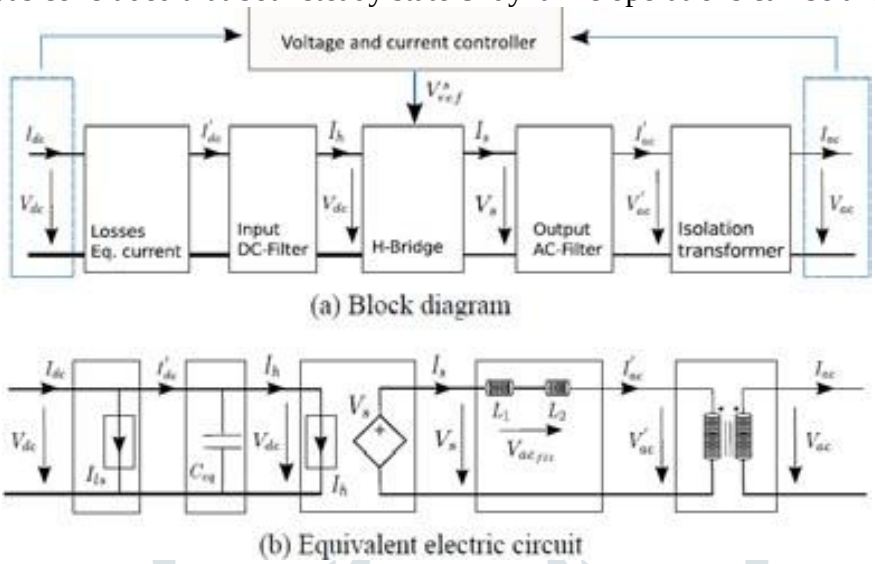
Figure 4: Main Simulink model operational flow diagram

Estimation (CSE), Event Triggered State Estimation (ETSE) and Event Triggered Tracking System (ETTSE). The methodology used was, consideration of IEEE 14 bus system where bus voltage, phase angle, active and reactive power flows were measured by the above estimation algorithms. Figure 6 shows 14 bus systems, Figure 7 shows variation in phase angle at bus 5 as calculated by different state estimation approaches. It was found that triggering estimation techniques were very fast & accurate as compared to classical ones for real term monitoring.

Quesada et al. [18] studied micro-grid with distributed energy storage. They proposed primary control for the inverters in a micro-grid. The inverters are connected to the micro-grids through R-L combination. The control methods used were decoupling droop control methods, which make frequency independent on active power. It was concluded that this control strategy provides efficient & faster dynamic response & maintains frequency & voltage

within specified limits.

Parez et al. [14] studied the modeling of grid connected photovoltaic inverters. The conventional inverter modeling is done without taking photo models & MPPT (maximum power point tracking) into consideration. But the behavioral model proposed takes solar irradiance & MPPT into consideration, due to which the standards of EN50160 power quality are met. Figure 5 shows proposed model with architecture & equivalent circuit. VCL (voltage control loop) & CCL (current control loop) are included in control architecture for correct voltage & current estimation. It was concluded that both steady state & dynamic operations can be analyzed.



(a) Block diagram

(b) Equivalent electric circuit

Figure 5: Model for current and voltage estimation

III. CONTROL TECHNIQUES

Francy et al. [15] explained the role of state estimation in the integrated power systems with variable energy resources. They compared different state estimation techniques like Classical State Ninad and Lopes [16] studied the control strategy for the mini-grids. The control used was vector control strategy for four-legged inverters. The voltage source inverter was controlled in a mini-grid to supply balanced voltages to highly unbalanced loads. Figure 8 shows the control block that was used for balancing the voltage levels in a mini-grid system. It was concluded that the control scheme was very fast to balance any imbalance in the load, so that specific voltage level was measured. Kumar et al. [17] proposed vector controlled isolated source cascaded two-level inverters for the grid-connected photo voltaic systems. The technique that was used to produce gate signals was simple pulse width modulation (PWM), because of its property of obtaining smooth wave shapes. Both the cases were examined, with equal & unequal DC-link voltage. It was found that the control method provided harmonic free inverter output voltages. The delivery of active & reactive power was achieved satisfactory by the vector-controlled schemes. In the absence of solar power, the control scheme acts as a DSTATCOM supplying reactive power to grid & led stabilizing the operation.

Quan et al. [19] studied the control strategy for the micro-grids. The micro-grids face various voltage fluctuation problems, severe & forward power flows, during more or less demand. They proposed a sinusoidal voltage signals tracking control for the I-Q inverters used in micro-grids. The methodology used for design of control algorithm was simulations based. Figure 9 shows the diagram of universal tracking controllers. It was concluded that the control strategy was adaptable to various frequency changes & it was easy to calculate controller parameters & it has quick dynamic response & provides stable operation for dynamic loads.

Khadem et al. [23], studied power quality in grids connected to renewable energy systems. There are various P-Q problems associated with renewable energy power penetration into grids. Table 2 categories the P-Q problems. These P-Q problems can be handled either on consumer side or on utility side. It was concluded that custom power devices can be used to mitigate P-Q problems UPQC, STATCOM and DSTATCOM has proved to tackle with various P-Q problems.

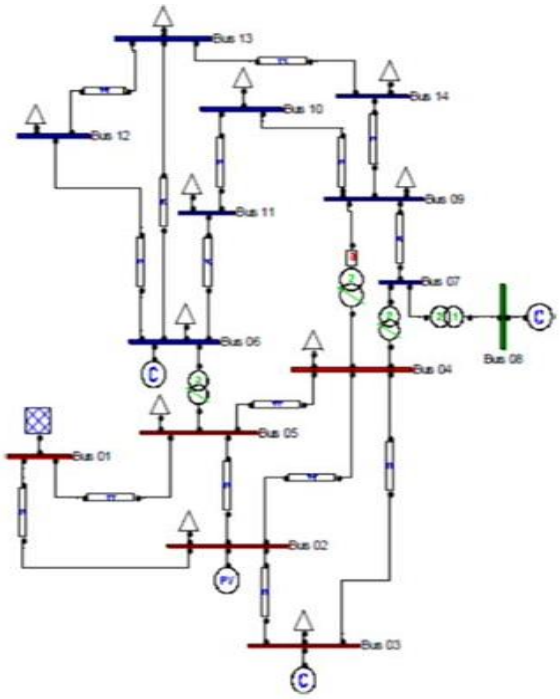


Figure 6: IEEE 14bussystem

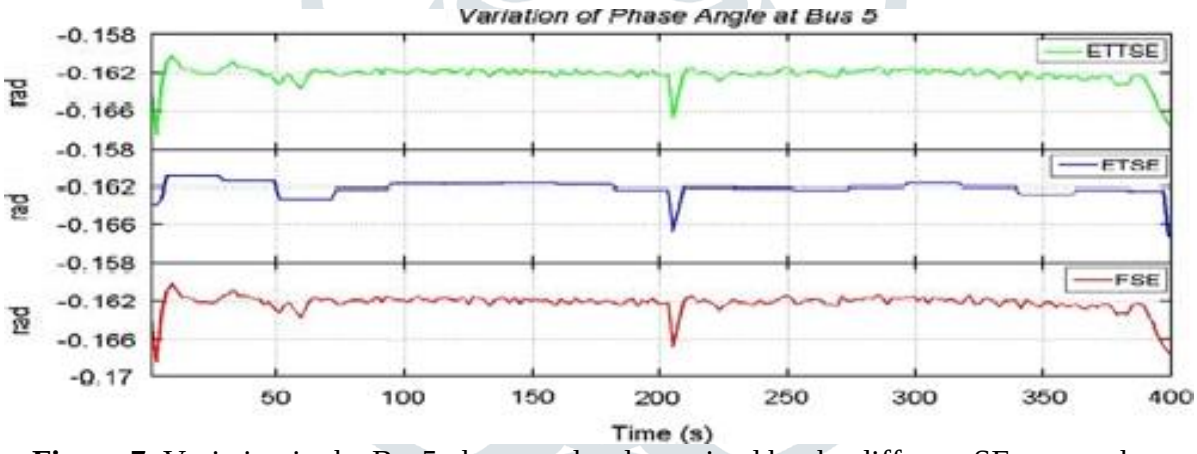


Figure 7: Variation in the Bus5 phase angles determined by the different SE approaches

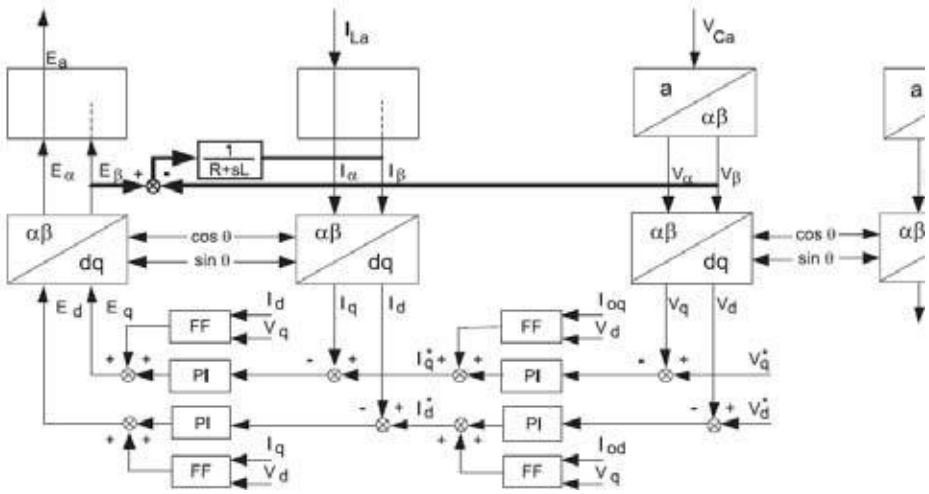


Figure 8: Schematic diagram of the per-phase cascaded control block

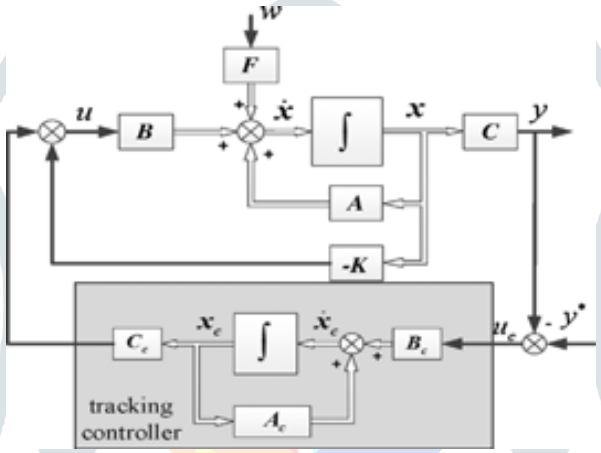


Figure 9: Universal tracking control diagram.

Schainker [20] studied various problems of renewable energy sources. The various problems associated with renewable energy sources are like oscillations, power fluctuations, de-stabilizing effect which put the already existing grids on stress. The solution for these problems was proposed to develop shock absorbers rather efficient energy storage methods, which are both cost effective & require minimum manufacturing volume. Compressed air energy storage (CAES) was found to be suitable for bulk power storage.

Smith et al. [21] studied the R&D requirements for wind integration. The energy produced from solar & wind is equally important like that of conventional energy but they are associated with uncertainty & variability. The technology used for making variable energy (solar & wind) dispatch able includes proper planning, flexible sources & metrics, deployment of high voltage direct current (HVDC), better energy storage methods, smart meters & other renewable technologies. Mostly in smart grid power electronic circuitry acts as interface between generators & transmission section. Further research is required for short circuit analysis in wind integration. For voltage & frequency control, it requires further more research. It was concluded that smart grid planning is totally different from conventional plants.

Hashim et al. [22] reviewed the various voltage control methods in both centralized & decentralized power systems. Since due to large penetration of DC sets or other sources in decentralized systems, there are large fluctuation problems with voltage & frequency. The various methods for voltage control discussed were OLTC (on load tap changing transformers), SVC (Static var compensators), STATCOM & other Fact devices. The role of excitation control was also discussed since voltage & reactive power have high affinity. The role of ANN (artificial neural networks) was also discussed for V & F control. For poor PF & load voltage consumers should be penalized. Figure 10 shows voltage at bus 2, with system modeled to DC connection. It was concluded that above methods are able to maintain bus voltages within permissible limits.

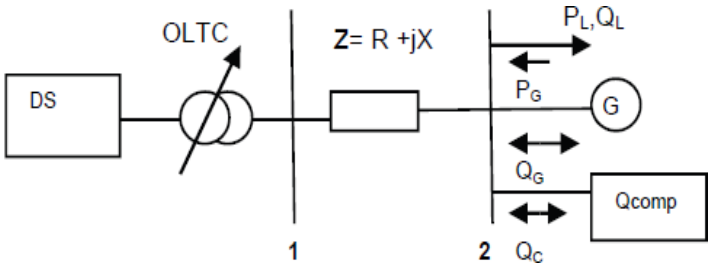


Figure 10: A simple system connected with DG to model voltage rise

Miguel Torrens and Luiz [24] studied the frequency related problems of diesel-based generator. Since increase or decrease of frequency has its ill consequences, so it is important to stabilize frequency. They make frequency stable by using virtual synchronous machine which adds damping & inertia to the system. However, the damping power formulation fails, when system operates in droop mode because of unknown stabilization value of grid frequency. It was concluded that estimator designed stabilizes frequency in droop mode.

Yan et al [25], observed the effect of distribution generation over the voltage magnitude levels at various nodes of the distribution networks. The technique used to study these effects is the sensitive analysis, in which it is being analyzed how one variable gets affected by the change of other. Same technique was used to check how voltage levels at various nodes change with the parameter changes on the source side (renewable generation side). Fig 11 shows distribution network which was under test and observation. It was concluded that sensitivity analysis helps in design of effective and efficient controllers.

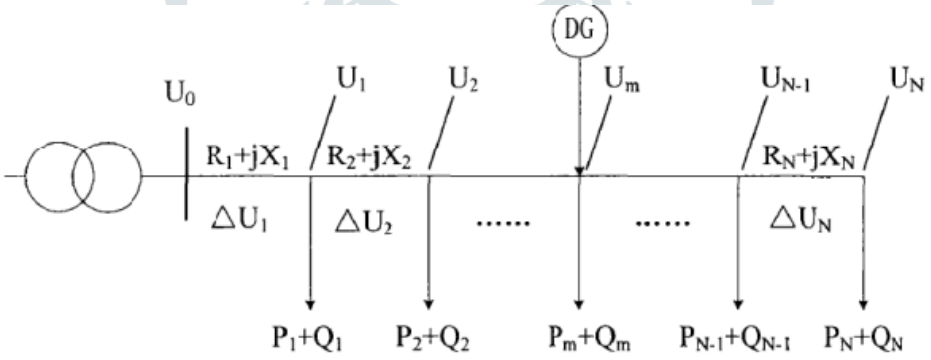


Figure 11: Distribution network with distribution generation

Shailder Kr. Tiware et al.[26] designed and implemented microgrid with solar and wind energy systems in integration with battery energy storage system, to meet the specified load demand at isolated place. Separate control strategy has been designed for every section. For solar section S-MPPT based control is used, for battery charging current vector control technique is used, for line and rotor side convertor stator current control techniques are used. Fig 12 shows line side converter control diagram. It was concluded that by using proper control techniques in micro and integrated systems, load demand can be satisfied in presence or in absence of renewable energy resources for short durations, for those short durations energy can be supplied from the battery systems, however efficient control needs to be in action to prevent batteries from deep discharges.

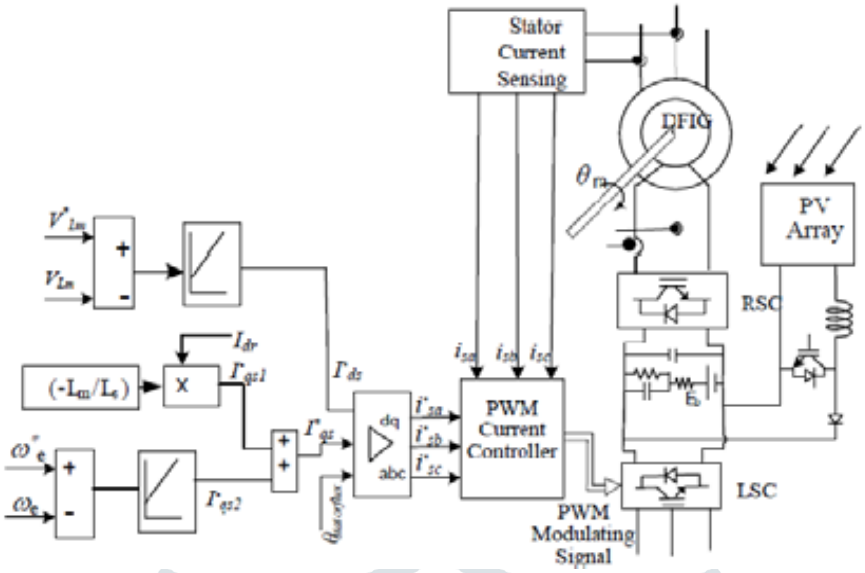


Figure 12: Line side convertor control diagram

Akshit and Kumari [27] performed MATLAB simulation of hybrid systems consisting of photovoltaic (PV), fuel cell and super capacitor energy storage system. The technique used by them for obtaining multi objectives like voltage control, charging and discharging control of energy storage system, harmonics control and power flow control. In order to achieve these objectives multiple controllers were used like droop controller, resonant inverter controllers and voltage controllers. Fig 13 shows control strategy for inverter. It was concluded that by using flexible and efficient control techniques multi objectives can be achieved in hybrid and integrated systems.

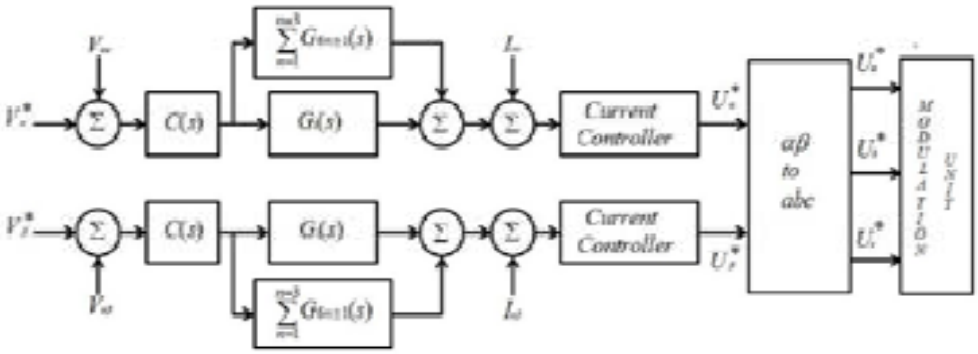


Figure 13: Inverter control strategy

Table 2- Categories of PQ Problems

Power Freq Disturbance	Electro Magnetic Interferences	Power system Transient	Power System Harmonics	Electrostatic Discharge	Power Factor
Low Freq phenomena Produce Voltage sag/swell	High freq phenomena Interaction Between electric and magnetic field	Fast, short duration event Produce Distortion like notch, impulse	Low frequency phenomena Produce waveform distortion	Current flow with different potentials Caused by direct current or induced electrostatic field	Low popup factor causes equipment damage

IV. Conclusion

This paper has discussed the renewable energy based integrated and hybrid systems. A review has been carried out to study various existing control techniques, to control the intermittent nature of renewable energy sources. Different control techniques like pulse width modulation, vector pulse modulation technique, stator and

rotor current control, tracking control, energy storage-based control, STATCOM and DSTATCOM based compensation control, power electronic circuitry-based power flow control, were highlighted in this paper for decentralization of power. Different observations made during review analysis are mentioned below.

- In majority of the simulation models Homer software was used, however there are many software available like power world, free mat, Minsky, Automation studio, Isaac dynamics, and hybrid, hybrid 2 which could be used for various modeling and simulation purposes, in order to get much accurate and faster results.
- Modern control techniques like fuzzy and neural based control techniques and heuristic search-based control technology could be used for the control action in integrated systems.
- The integrated system could be made adaptive to environmental changes by using various machine learning.
- Super conducting magnetic energy storage, hydrogen storage, storage coil, cryogenic energy storage, molten salt could be used for maintaining the frequency and voltage parameters citing the intermittent nature of renewable energy resources.
- For real time-based control, phase measurement units (PMU), wide area measurement units (WAMS) should be implemented for measurement purpose.
- Sensitive approach based contingency analysis should be done to check the correlation between different parameters.
- Robust and dynamic state estimation techniques should be used for state estimation.
- Interoperability and smart communication should be used for transferring control signals over the networks.

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