“Control Strategy of AC/DC Hybrid Micro-Grid for Optimal Power Flow Management”

Ph.D. Synopsis

Submitted To

Gujarat Technological University

By

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Contents

1. Objectives of this Work (ABSTARCT)

- To propose and develop a hybrid AC/DC micro-grid (with combination of Photovoltaic (PV) and a hydrogen storage system as backup) that consists of both ac and dc networks connected together by bidirectional converter.
- The Proposed Hybrid micro-grid would improve the dynamic performance of the Grid connected PV System (GPVS) in a day ahead market.
- This work deals with system integration and controller design for power management of a grid connected Microgrid system.
- A two level control system is implemented, comprising a supervisory controller, which ensures the power balance between intermittent PV generations, Hydrogen based energy storage, and dynamic load demand, as well as local controllers for the photovoltaic, electrolyzer, and fuel cell unit.
- The coordination control algorithm is proposed for smooth power transfer between ac, dc links and Tie Line for stable system operation under various generation and load conditions.
- Profile of AC and DC bus voltages has been analyzed especially, when the operating conditions or load capacities change under the various modes of operation.
- The proposed Microgrid can be advantageous in a distribution system having voltage fluctuations in close vicinity to the solar Farm.
- The control strategy has been proposed for voltage regulation utilizing proposed Microgrid as static synchronous compensator (STATCOM).
- In grid connected mode, power can be imported from the grid to charge the electrolyzer or it can be injected into the grid to boost the power supplied by the Microgrid to contribute the frequency stability.
- MATLAB/ SIMULINK based simulations have been carried out and results are provided to show the effectiveness of the proposed control strategy.

2. State of the Art of the Research Topic

It has become extremely important to think for alternative renewable resources [1-2] such as wind, photovoltaic (PV), fuel cells (FC), small hydro, bio-fuels etc. These distributed generation has been integrated into the distribution system which emphasizes over optimal operating strategy [3-6]. Their demand is further enhanced due to encouragement of the ongoing deregulation in the generation sector [2].

Earlier power to the distribution system was supplied by a single substation, but now the distribution system may have numerous generators feeding various customers. Addition of multiple generators in the distribution system can result in instability. Thus, such a distribution system is under a threat of voltage and frequency drift (as on the transmission grid when there is no tertiary control), or even of losing synchronism.

In this work the hybrid micro-grid is proposed that is composed of a PV generator, local loads, Hydrogen based electricity storage (Electrolyzer) and SOFC (Fig.1).

Although considerable advances in hydrogen related technologies (electrolyzer, fuel cells, and storage media) have occurred during recent years, significant barriers in system integration must be overcome before the potential of renewable resource/ hydrogen buffered energy systems can be realized. The proposed hybrid micro-grid is as below.

A. 100 kW photovoltaic array
B. 50 kW SOFC (Solid Oxide Fuel Cell)
C. 50 kW Alkaline Electrolyzer
D. VSC 100 kVA
E. AC Load 10-50 kW and 0-20 kVAR.
F. DC Load 0-20 kW

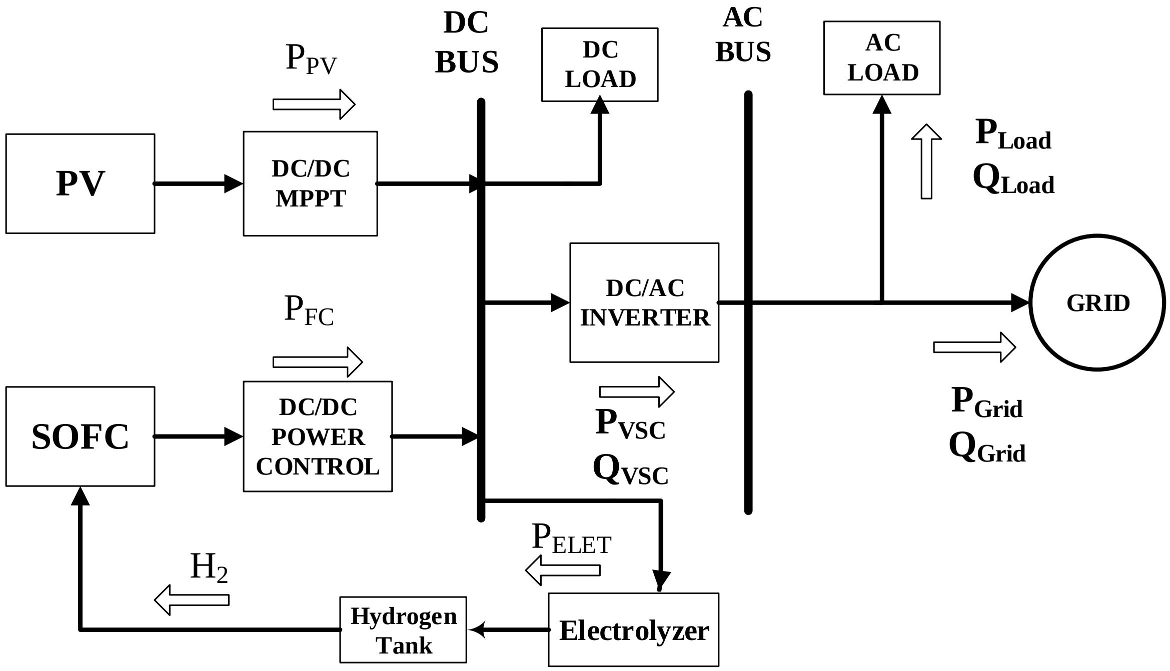

Fig.1 Block Diagram of the proposed Hybrid Microgrid scheme

WORK DONE

- Problem Identification and Literature Review.
- Developed model for PVECS (Photovoltaic Energy Conversion System) for 25kW, 50kW and 100kW and verified characteristics with MPPT.
- Developed Model of grid connected Inverter for independent control of Active and Reactive Power.
- Control strategy for Grid connected PV System (GPVS) with Power factor and MPPT control.
- Detailed modeling of SOFC for 50kW
- Detailed Modelling of Duty cycle of Parallel DC converter and PLL.
- Developed HPVFCS (hybrid PV and FC System) MG using PV and FC with Reactive Power Compensation Feature.
- Added Hydrogen storage -Fuel Cell &Electrolyzer system) - Control Strategy for Utility Interactive Hybrid PV Hydrogen System (HPVHS - hybrid AC/DC micro-grid).
- Developed Control Strategy for direct and indirect grid voltage regulation utilizing proposed Microgrid as static synchronous compensator (STATCOM).

3. Definition of the Problem and Original contribution by the thesis (Literature Review)

Large scale GPVS (Grid connected PV System) are being connected to the grid. However, integration of PV imposes significant challenges to grid operators, due to mismatch between maximum generation and maximum demand, which can result in grid instability, negative pricing, and wasteful curtailment [4]. Thus PV generation makes grid management difficult. Hence, PV production into the grid is considered to be limited [1-2]. To solve these problems, a combination of GPVS together with grid scale energy storage system improve the security of supply considerably [3] and, as a consequence, the overall operational efficiency of the utility. Grid scale energy storage enables further growth of PV by (1) levelling peak load, (2) increasing the capacity factors of solar installations, and (3) transforming these intermittent GPVS into grid dispatchable resources.

A variety of grid scale storage technologies including pumped hydro, compressed air, and various types of battery Storage etc. with sufficient dynamic responses have been investigated [3-5]. However lithium ion batteries remain preferable when considering the (i) operation of the system (ii) its manufacturing (iii) their higher round-trip efficiency (90%). But the Physical size, limited life span, and initial capital cost of the battery bank coupled with transportation, maintenance, and battery disposal issues imposes significant limitations on the load capacity [6]. Another technology available for grid scale energy storage is a regenerative fuel cell, in which energy is stored as hydrogen gas [6].

Hydrogen is an attractive energy carrier since it is one of the cleanest, lightest, and most efficient fuels, but it has a slow power response time [3-4]. The disadvantage of the slow dynamics can be compensated by implementing a suitable power management tool. The cost of energy storage in a regenerative hydrogen fuel cell is already potentially competitive with batteries in an optimized energy arbitrage system [6-7].

In this work the HPVHS (Hybrid PV Hydrogen System) is proposed that is composed of a PV generator, local loads, Hydrogen based electricity storage (Electrolyzer) and SOFC. Large number of RHFC projects have already been implemented hydrogen storage, spanning a wide range of energy and power capacities [7-11]. Significant research efforts have been devoted to the modeling and control of individual process components as well as integrated systems [12-17]. **The integration issues associated with the development of a hydrogen energy buffer are not well understood or documented in the literature. Furthermore, and perhaps more importantly the dynamic interactions between system components that occur while servicing real world loads remain unexplored.**

This HPVHS system is connected to the grid by a Voltage Source Converter (VSC) can perform many Grid Support Functions like Voltage Balance services, Spinning Reserve, Peak shaving technology and reactive power support [3], [19-20]. However, the integration of grid connected storage is currently limited by two constraints. 1) Regulations: The present VSCs are complying with IEEE 1547 and do not take part in any other Grid support activities [19-20]. But it is expected that regulations will become more flexible as in the example of the new German feed-in law from EGG [21]. 2) Power Flow Management: An electrical storage element generates expensive investment and operation costs with strong operating constraints.

A novel research has been reported on the night time usage of a PVS (when it is normally inactive) where a PV solar farm is utilized as a Static Compensator (STATCOM) [20,22], a FACTS device for performing voltage control, thereby improving system performance and increasing grid connectivity of neighboring wind farms. It is known that voltage control can assist in improving transient stability and power transmission limits [22], several shunt connected FACTS devices, such as, and Static Var Compensator (SVC) and STATCOM are utilized worldwide for improving transmission capacity. Many industries use some kind of active power factor compensation to match the power factor regulations in developed countries. In these cases, the high cost of these active systems can be partly paid by connecting HPVHS system in its dc side. On the other side Grid connected HPVHS can provide additional function of Power Factor correction, UPS and/or STATCOM.

The novel idea proposed in this thesis is that HPVHS while supplying real power output is made to operate as a STATCOM and provide direct and indirect grid voltage control using its remaining inverter MVA capacity (left after what is needed for real power supply.

4. Methodology of Research (Control Architecture)

The aim of this Research Work is to present a comprehensive study of the automation system design [23] for a Grid connected HPVHS. Multilevel control scheme has been reported as a more practical and efficient hierarchy for controlling hybrid energy systems [24-26]. Hybrid system with the use of PV and FC sources has been proposed in [27, 28] in which PV and FC sources are connected to a utility through two Voltage Source Converters (power inverters). A better system has been proposed in [3, 29] which overcomes the drawbacks of the earlier ones [27, 28]. Paralleling of dc–dc converter is better than paralleling of inverters having advantages of (i) stable dc bus voltage (ii) controllable power devices reduces and hence switching losses are decreased and, the overall reliability is increased [3].

The optimal integration of hydrogen storage with GPVS (Grid-connected PV System) and the power management of such systems (paralleling of dc–dc converter) have also received considerable attention [13-15]. The importance of this control strategy for the optimal operation of the photovoltaic (PV)/hydrogen/battery systems has been shown [29]. In the proposed HPVHS system, dc-dc and dc-ac converters are used to interconnect outputs from the various generation sources of a hybrid energy system and grid (with loads).

Several control schemes [30] for the control of parallel DC converters have been reported in the literature , the main schemes are droop control [30], [31] and active current sharing methods [32], [33]. The major problems associated with these schemes are voltage regulation, load sharing and circulating current [34]. Circulating current leads to further increased flow of current through the switches which in turn increases the power electronic switch ratings and losses. Circulating current also gives rise to a difference in current sharing which causes an overload on the converters.

A novel droop algorithm is reported in [30] for the converter parallel operation. A decentralized circulating current control method is proposed in [35], which is based on no-load circulating current values. This will reduce the error in current sharing without deteriorating voltage regulation. **The applied control structure for the system developed here**

(Paralleling of dc–dc converter) consists of two layers: the supervisory controller and local controllers.

4.1 Supervisory Power Control

All process subsystems and their controllers are connected to the supervisory controller. The supervisory controller ensures the power balance between power generation (PV and/or FC), energy storage (Electrolyzer), and dynamic load demand (including auxiliaries' consumption) at each sampling time interval by Activation and Deactivation of the electrolyzer or fuel cell based on the various modes of operation. The supervisory controller also computes the power references (operating trajectories) for the fuel cell (P_{FC}), electrolyzer (P_{ELET}) and VSC (P_{vsc} & Q_{vsc}) subsystems.

4.2 Local Decentralized Controller (LDC)

Each component (PV, SOFC, electrolyzer and VSC) in the proposed HPVHS has its own local decentralized controller (LDC) that implements power control over it. The power references **(**table 1**)** from the supervisory controller are sent to corresponding LDC system, which brings them to the desired power reference values while minimizing a suitable cost function, improve efficiency and optimize its performance by effectively utilizing PV power. Each controller determines the constraint-admissible and optimum value of the current that can be applied on the electrolyzer/SOFC at each sampling time. The local controller is also responsible for regulating five control variables (process component) such as Duty Cycles of DC Converter (D_{PV}, D_{FC}, D_{ELCT}) and power angle & Modulation Index of VSC (M and δ) that will reduce the error in current sharing without deteriorating voltage regulation based on the available information of power generated from the PV, fuel cell, electrolyzer, VSC and power demand.

5. System Component Characteristics

In this section, the characteristics of the aforementioned (Fig.1) main system components are discussed.

5.1 MPPT operation of PV [20]

The PV panels are connected to the DC – Link through a DC/DC converter.

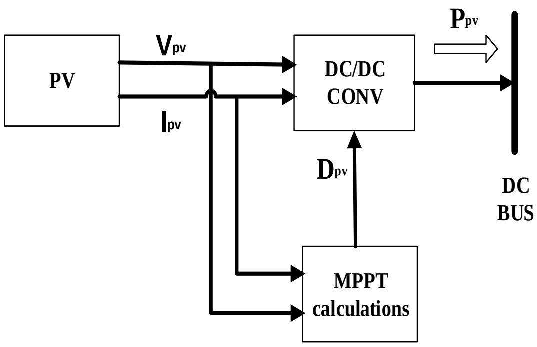

Fig.2 MPPT Operation of PV

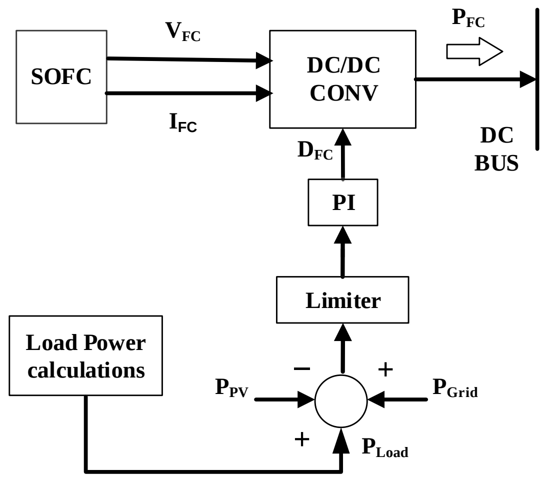

Fig.3 Control of SOFC Power

By applying PWM control scheme with appropriate Maximum Power Point Tracking (MPPT) algorithm (Perturb & Observe) the converter draws maximum power from the PV array under different solar irradiation [37-40], [42] Power Generated by PV (P_{PV}) can be given as

$$P_{PV} = I_{PV}V_{PV} \qquad (1)$$

$$P_{PV} = I_{PV}V_{DC}\,(1 - D_{PV}) \qquad (2)$$

Where V_{PV} and I_{PV} are PV array voltage and current respectively. V_{DC} is the inverter's dc bus voltage and D_{pv} is the duty cycle of the PV side boost converter. D_{PV} is governed by MPPT independently hence maximum power P_{PV} is transferred under all conditions [20] as shown in Fig.2.

__5.2__ Control of SOFC Power [43]

SOFC system is connected in parallel with PV to a common dc bus through DC-DC boost converter as shown in Fig.3 that supplies system deficit power [44-46]. The SOFC (rated power of 50 kW) model developed in this work has been based on [43]. Power supplied by Fuel Cell (P_{FC}) can be given as

$$P_{FC} = I_{FC} V_{DC} \, (1 - D_{FC}) \tag{3}$$

Where I_{FC} is the FC stack current and D_{FC} is the duty cycle of the FC side boost converter. Any power deficit between ($P_{Load} + P_{Grid}$) and P_{pv} is to be supplied by the FC stack through control of D_{FC} as shown in Fig. 3.

$$P_{FC} = (P_{Load} + P_{Grid}) - P_{pv} \tag{4}$$

5.3 Control of Electrolyzer Power [47]

An electrolyzer is a device that produces hydrogen and oxygen from water. The modelled electrolyzer type is a so-called advanced alkaline electrolyzer [47]. In order to achieve maximal hydrogen generation, the DC/DC converter is placed between the electrolyzer and the DC – Link is controlled by a separate controller. H_2 is directly produced at 99.9% purity. Also the current efficiency is 100%, and hence the hydrogen production rate [48] is:

$$X_{H_Z} = 5.18e^{-6} \, I_{ELET} \;\; \text{mole/s.} \tag{5}$$

Where I_{ELET} is the current between electrodes.

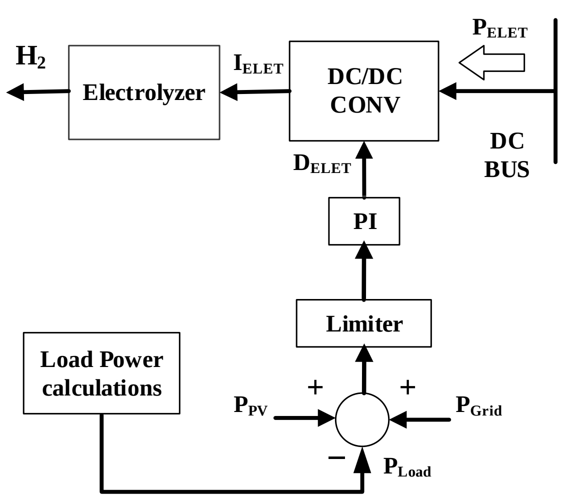

Fig.4 Control of Electrolyzer Power

Any surplus power between (P_{pv} + P_{Grid}) and P_{Load} is to be stored in an electrolyzer as shown in Fig. 4.

$$P_{ELET} = (P_{pv} + P_{Grid}) - P_{Load} \quad (6)$$

5.4 Three Phase DC to AC converter (VSC) Control [49]

Two control variables (M is the Modulation index and δ is the power angle) are available that provide change in Active Power (P_{vsc}) and Reactive Power (Q_{vsc}) outputs of VSC [49, 50]. The controller is composed of two proportional-integral (PI) based regulation loops [51].

A. Active Power Control

The job of maintaining the DC link capacitor voltage is done by the DC link voltage regulating control systems (Fig. 5) [49, 50]. Power angle (δ) is kept lagging so as to take real power from the grid. Under steady state conditions, power angle is constant and leading to supply power to grid.

B. Reactive Power Control

For positive VAR (supply of reactive power), VSC voltage has to be higher than the grid voltage. Increasing the modulation index of the SPWM waves serves the purpose. And similarly for negative VAR (take/absorb the reactive power), modulation index has to be decreased. The VSC can be operated in two different modes:

I) In voltage regulation mode (the voltage is regulated within limits as explained below): As long as the reactive current stays within the minimum and maximum current values ($-I_{max}$, I_{max}) imposed by the converter rating, the voltage is regulated at the reference voltage V_{ref} (Fig. 5) [50].

II) In Var control mode: The VSC reactive power output is kept constant [50] (Fig. 6).

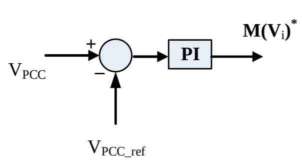

Fig. 5. Voltage regulation mode for Reactive Power Control

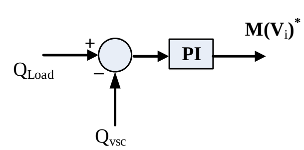

Fig. 6. Var control mode for Reactive Power Control

6. Achievements with respect to objectives (Results and Discussions)

6.1 *Various Modes of operation (TABLE 1) [52]*

Mode I: HPVHS TO SUPPLY CRITICAL LOAD RELIABLY ($P_{Grid} = 0$)

Mode I (A): PV-Electrolyzer

Mode I (B): PV- FC

Mode I (C): Only FC

Mode II: UTILIZATION OF HPVHS TO REGULATE PCC VOLTAGE as STATCOM (Direct Grid Voltage Regulation)

Mode III: PROPOSED UTILIZATION OF HPVHS TO REGULATE PCC VOLTAGE and POWER FLOW IN FEEDER. (Indirect Grid Voltage Regulation)

TABLE I
Active Power Management for various Modes of HPVHS

	Power generated by PV	Power stored in Electrolyzer	Power supplied from FC	Power delivered to Load	Power delivered to Grid
Mode I(A) $P_{pv} > P_L$	P_{PV}	$P_{PV} - P_{Load}$	0	P_{Load}	0
Mode I(B) $P_{pv} < P_L$	P_{PV}	0	$P_{Load} - P_{PV}$	P_{Load}	0
Mode I(C) Night	0	0	P_{Load}	P_{Load}	0
Mode II		As per modes I			
Mode III	P_{PV}	Mod ($P_{PV} + P_{Grid} - P_{Load}$)	Mod ($P_{Load} + P_{Grid} - P_{PV}$)	P_{Load}	P_{Grid}

To demonstrate the working and feasibility of the proposed HPVHS scheme, a model has been built and simulated in MATLAB/SIMULINK for a power rating as discussed in section II. The HPVHS is simulated in all the three operating modes described in section VI and the corresponding results are discussed next. The parameters of the PI controller are computed with the help of Ziglar-Nicholas method.

6.2 Simulation of HPVHS for change in Irradiance 1000 W/m^2 to 250 W/m^2 (Mode I)

Simulation results (Fig. 7) show the transients in various parameters due to variations in solar irradiance from 1000 W/m^2 to 250 W/m^2. The DC bus voltage of the inverter is maintained at 700V, Load on DC bus (P_{L_DC}) is 20 kW and on AC bus (Active Power Load on Ac bus - P_{L_AC}) is 30 kW and (Reactive Power Load on Ac bus - Q_{L_AC}) 20 kVAR during the simulation. As discussed in section III all power generated by the PV (with MPPT) is supplied to the DC bus.

For any change in the value of Irradiance (increase or decrease), there is a change in the power generated by the PV array. As a result, current fed by the DC–DC converter into the DC bus also changes. It is important to note that V_{DC} also changes during these changes in irradiance, but the control circuit restores it to its reference value 700 V. Initially, the solar irradiance is maintained at 1000 W/m^2 (Fig. 7), hence HPVHS is operating in Mode I (A): (PV-Electrolyzer). P_{PV} (100kW) is greater than P_{LOAD} (Total System Load on AC and DC bus), the extra power (P_{PV} - P_{Load}), neglecting losses is stored in the electrolyzer (P_{ELET} = 50 kW approx.) for producing hydrogen and the VSC will feed the load power at the AC bus (P_{L_AC} & Q_{L_AC}). Power Supplied to the grid (P_{Grid}) is zero. When the irradiance starts decreasing from 1000 W/m^2 and reaches 250 W/m^2, P_{PV} also decreases according to irradiance and reaches its new maximum power point (MPP = 25 kW) (Fig. 7). In an actual system, this rate of change of PV power variation depends on several factors like variations in ambient temperature and the cloud movement velocity. As P_{PV} starts decreasing, no effect on P_{VSC} that supplies load on AC bus (30 kW + 20 kVAR). Once P_{PV} is less than P_{Load}, the FC stack starts supplying the power. Thus, any deficit between P_{Load} and P_{pv} (25 kW) is supplied by the FC source. The variation in D_{FC} to supply the required power is not shown here as it is discussed in [3]. At the instant when the FC starts supplying the power, the HPVHS shifts from Mode I (A): (PV-Electrolyzer) to Mode I (B): (PV- FC). To highlight an important point regarding the operation of the FC stack, at the irradiance 250 W/m^2, the PV array settles to the new MPP which is much less than P_{Load}, hence the transients are observed in P_{VSC}. Authors in [3] show a steady ripples in D_{PV}, this is due to the "perturb and observe" algorithm employed by the MPPT technique and the power balance carried out by the inverter at its DC bus.

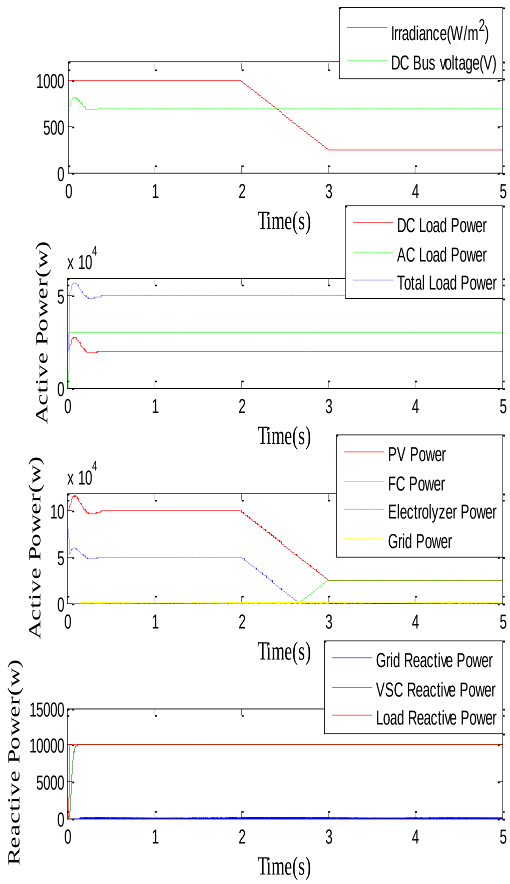

Fig. 7 Simulation of HPVHS for change Irradiance 1000 W/m^2 to 250 W/m^2

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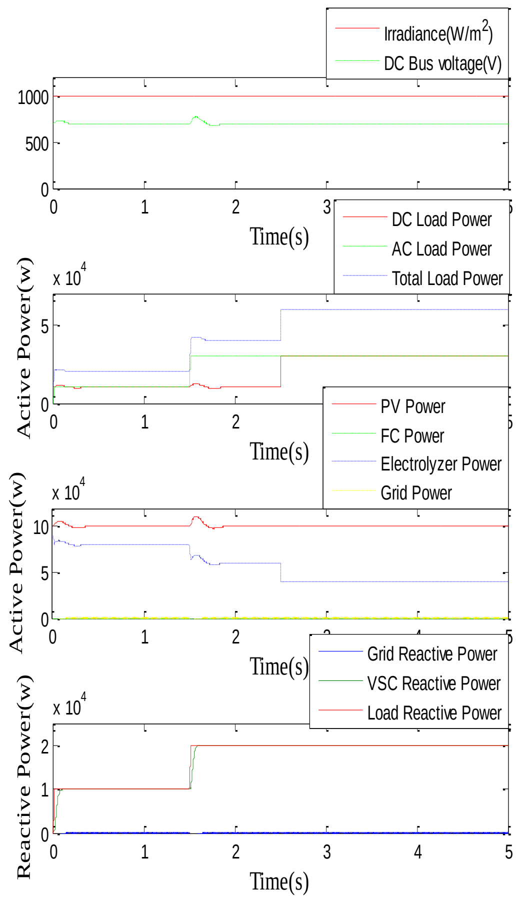


Fig. 8 Simulation results of the HPVHS for Load on AC bus at t =1.5 s changed from (30 kW + 10 kVAR) to (50 kW +20 kVAR) and on DC bus at t = 2.5 s from 10 kW to 20 kW

6.3 Simulation results of the HPVHS for Load change on AC bus and on DC bus (Mode I).

V_{DC} is maintained at 700 V, irradiance 1000 W/m^2, Load on AC bus at t =1.5 s changed from (30 kW + 10 kVAR) to (50 kW +20 kVAR) and on DC bus at t = 2.5 s from 10 kW to 20 kW as shown in Fig. 8. Effect of any change in load is met optimally. If HPVHS is operating in mode I, PV Power must be utilized first and then FC power if required only. Fig. 8 shows P_{vsc} follows the sudden change in Load on AC bus (P_{L_AC} & Q_{L_AC}) very closely highlighting the effectiveness of the control circuit. Effect of change in load on DC bus effects more on DC bus voltage than change in load on AC bus.

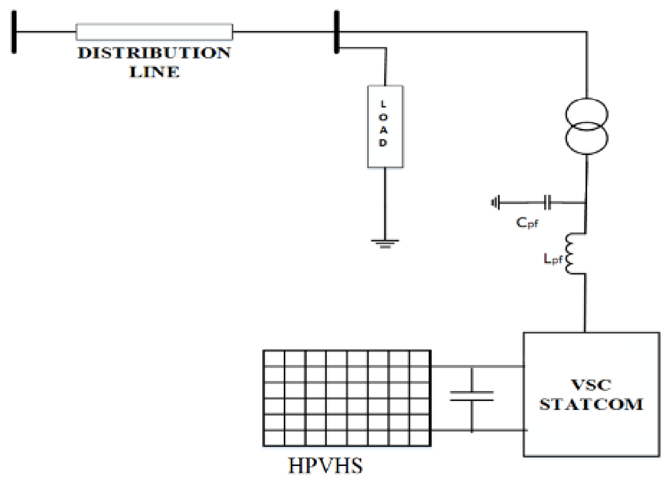


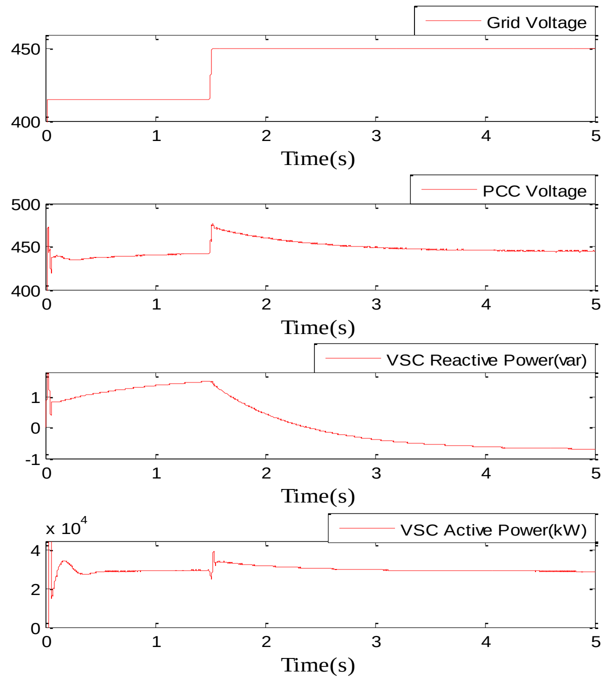
Fig. 9. Basic Block Diagram OF HPVHS as STATCOM [50]

6.4 Grid Voltage Rise from 415V to 450V. (Mode II)

The bidirectional inverter of the HPVHS is operated as STATCOM to regulate the PCC voltage by providing leading or lagging reactive power during bus voltage drop and rise, respectively (Fig.9). At t= 1.5 sec, when grid voltage falls from 415V to 400V, voltage across point of common coupling changes from 440V to 425V that is less than normal voltage ($V_{Nominal}$)[Fig. 10]. The VSC supplies the reactive power to make V_{PCC} again 440V. Decreased PCC Voltage tends to decrease VSC Active Power (P_{VSC}), control strategy brings back it to set value.

6.5 Grid Voltage fall from 415V to 400V. (Mode II)

At t= 1.5 sec, when grid voltage falls from 415V to 400V, voltage across point of common coupling changes from 440V to 425V that is less than normal voltage ($V_{Nominal}$)[Fig. 11]. The VSC supplies the reactive power to make V_{PCC} again 440V. Decreased PCC Voltage tends to decrease VSC Active Power (P_{VSC}) control strategy brings back it to set value.



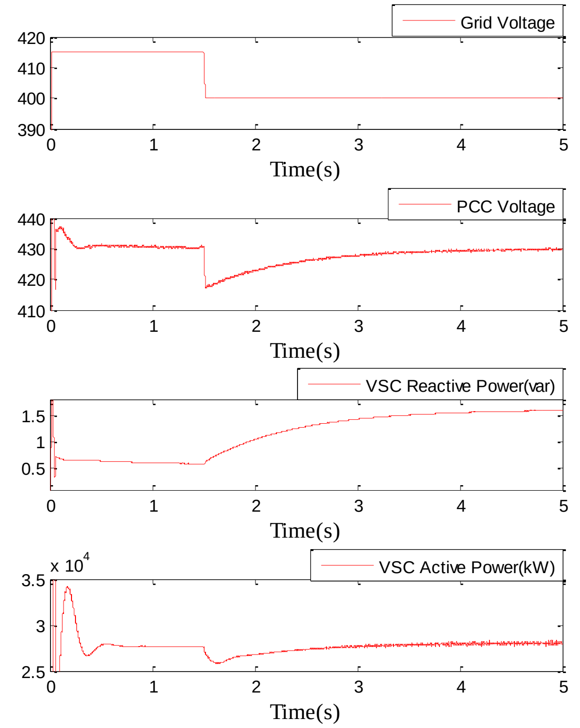
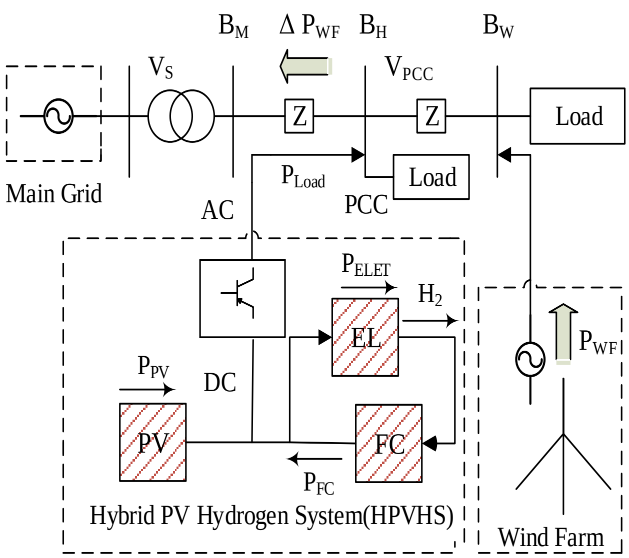


Fig. 10 Grid Voltage Rise from 415V to 450V

Fig. 11 Grid Voltage fall from 415V to 400V

6.6 Power Delivered to Grid (P_{Grid}) (Mode III)

Considering the distribution system consisting HPVHS and wind farms (100 kW) connected on the same feeder. (Fig.13).



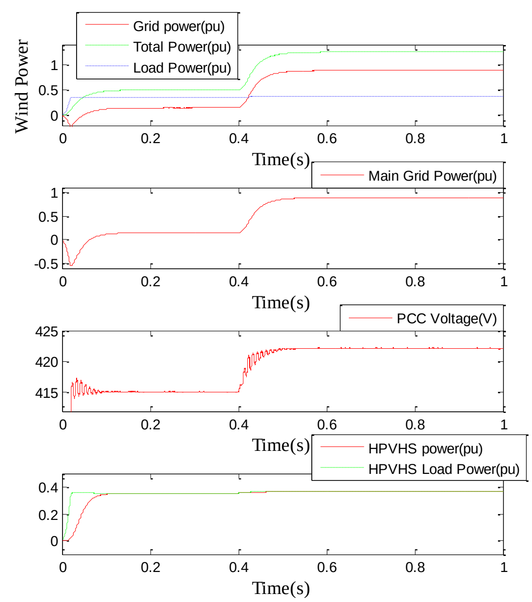


Fig. 12 Utilization of HPVHS Mode III during night with no Interaction

(i) During night-time:

Here HPVHS and wind farm supply the load bus at bus B_H (15 kW) and B_W (20 kW). Initially wind generated power (P_{WF}) is 25 kW so the surplus power ($\Delta P_{WF} = P_{Grid}$) 5 kW flows back towards the main grid (from B_H to B_M) and when wind power increased to 60 kW the power delivered to grid is 40 kW as shown in Fig 12 causing voltage to rise at PCC (V_{PCC}) from 415V to 423V if there is no interaction between HPVHS and wind Farm.

As it is proposed for Mode III When the voltage at PCC (at B_H) is rises and real power flow to main grid (from B_H to B_M) gets reversed, the electrolyzer charging loop is activated. Part of the wind generated real power initially 5 kW and later 20kW (ΔP_{WF} - P_{Load}) is extracted and utilized to charge the electrolyzer such that the voltage at PCC will be regulated (415 V) as shown in Fig 13 (1 pu = 50 kW).

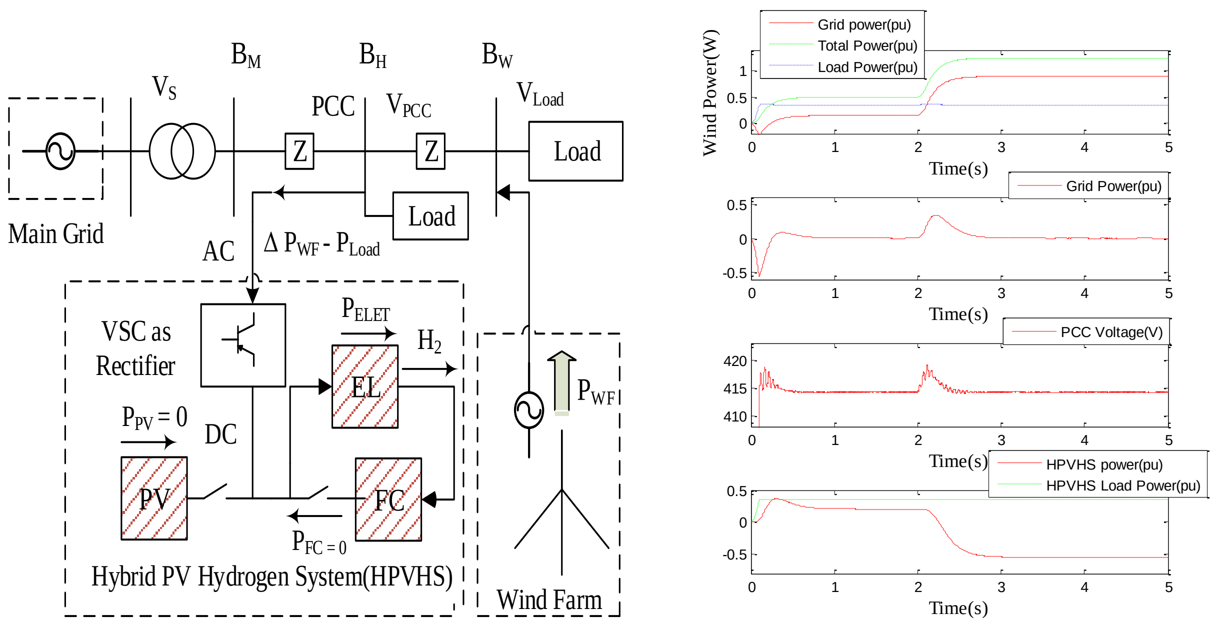


Fig. 13 Utilization of HPVHS Mode III during night with Interaction.

(ii) During day and Peak hours' time:

The deficit power ($\Delta P_{WF} = P_{Grid}$) flows back from the main grid (B_M to B_H) causing voltage to fall at PCC (V_{PCC}). As it is proposed for Mode III, when the voltage at PCC (at B_H) falls and power flow from main grid (from B_M to B_H), during the day-time (peak hours) this stored energy in the electrolyzer ($\Delta P_{WF} + P_{Load}$) is delivered back to the PCC and voltage at PCC is brought back to normal (415 V).

7. Conclusion

A PV solar based distributed generation system with Hydrogen based storage (HPVHS –Hybrid Microgrid) has been proposed in this research that can supply local load (both Active and Reactive Power) reliably. The HPVHS inverter can be operated as a STATCOM to regulate voltage of PCC by supplying/absorbing reactive Power. A new concept for feeder voltage control is presented in which the voltage rise (due to a substantial amount of reverse power flow from the wind farm and other reasons) is controlled by utilizing the HPVHS inverter as three phase controlled rectifier to charge the electrolyzer (generation of Hydrogen). In future work, the proposed approach will be expanded for a medium voltage, large scale HPVHS based distribution system and contribution of such microgrid for voltage stability enhancement in a large power system can also be investigated.

8. Four papers published

1. Mr. Vinod S. Tejwani, Dr. Bhavik N. Suthar "Power Management in Fuel Cell based Hybrid Systems" International Journal of Hydrogen Energy (Elsevier). 42 (2017) 14980-14989

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