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An Analysis of the Performance of a Grid-Connected Hybrid Power Generation System Combining Wind and SOFCs, with an Ultracapacitor Storage Unit

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***Abstract* - This paper explores the usage of hybrid power generation system based on a Solid Oxide Fuel Cell (SOFC), Wind, and an Ultra-Capacitor (UC) in a grid-connected scheme. The UC acts as an energy storage system to compensate for the slow dynamic response of the SOFC. This combination of components effectively maintains a stable output of power from the Wind system. Control systems are implemented to manage the power converters associated with the energy system to meet the expected demand. The SOFC needs to increase its power in the face of changes in the inverter power or a decrease in Wind power, and in both cases, the UC supplies energy until the SOFC reaches the desired power output level. Recharging of the UC is done using Wind power. The hybrid system is capable of providing constant power irrespective of fluctuations in wind speed. Results obtained from simulations are presented to demonstrate the performance of the hybrid system with respect to the changing wind speed and load.**

Keywords: Wind Energy, SOFC, Grid Connected, Hybrid System.

I. INTRODUCTION

The demand for electrical power is increasing rapidly while meeting the increasing demand at the same pace is difficult due to economical, environmental and time constraints associated with building new power plant. The strive for clean power generation has became a priority for energy sector due to increased awareness regarding environmental issues on using fossil fuels. Clean energy generation and reducing the demand-generation gap can be achieved using small scale generation placed near the load centre. The power generation in range of few kilowatts to a megawatts are termed as distributed generation (DG) [1]. The distributed generators are placed near load centre and have advantages like utilization of local resources, reduction of stress on distribution system, voltage support. However the DG can affect the system adversely if proper care is not taken in sizing and placement [1]. The distributed generation based on renewable resources uses naturally available resources to produce electricity such as PV (photo voltaic), wind, tidal, geothermal. The fuel cell and micro-turbine are the DG's gaining importance nowadays due to high efficiency and combined heat and power applications.

Among the renewable based distributed power generation the PV and wind has gained more importance and has well established technology. The wind system is one of the old technology utilizing wind power to generate electrical power. The wind based power generation has disadvantage as the output is fluctuating as wind speed varies widely, seasonally and timely [2]. However the load requirement is constant hence wind systems are associated with energy storage systems. The batteries are commonly used as storage system with wind system to store the energy when the wind power is available and release it as per load requirement. The system output is limited by wind power availability, battery capacity and it's state of charge. The batteries are high energy density devices and suitable for constant output requirements. However as wind varies widely the battery also undergoes uneven charging and discharging cycle which affects the life of battery [3]. In order to support the battery life the UC are used [4]. The ultra- capacitor is a high power density device, able to deliver the burst of power instantly and can undergo high number charging/discharging cycles. The better way to tackle the issue with wind system is to combining different resources to supply constant power. The combining different resources leads to hybrid generation system.

AI-based technologies are gaining prominence as a means

of efficient and sustainable energy generation. Hybrid energy systems, combining fuel cell and renewable energy sources like PV and wind energy, offer a promising solution to achieve reliable power generation while mitigating the variable output of renewables. SOFCs are gaining popularity due to their high efficiency and environmental friendliness. However, the slow dynamic response of SOFCs can be an obstacle when it comes to timely responding to changes in the output due to load or wind speed. The incorporation of ultra-capacitors in a hybrid system can mitigate this problem. By combining the wind system, fuel cell and ultra-capacitor, the fluctuating power generation from wind as well as the slow dynamic response of SOFCs can be mitigated. The SOFC supplies deficit power during low wind speeds, while the ultra-capacitor aids in smoothing out changes in the output due to load or wind speed. Furthermore, efficient utilization of the wind system can be achieved by taking advantage of the capability of ultra-capacitors to absorb and store the energy generated by the wind system. This hybrid combination makes the resulting energy system more reliable, efficient and sustainable, while also making it environmentally friendly.

The Hybrid System is an energy generation technology developed to provide both reliable and sustainable power. It consists of a Solid Oxide Fuel Cell (SOFC), Variable Speed Wind Turbine with Permanent Magnet Synchronous Generator (PMSG) and Ultra-capacitor, all interconnected in order to achieve the desired result. First, the SOFC and wind turbine are connected to a common DC-link, with a DC-DC boost converter regulating the flow of electricity. The PMSG is then rectified into a direct current (DC) by a diode rectifier that is also connected to the DC-link through the DC-DC boost converter. Finally, the whole hybrid system is connected to the grid via an inverter. Control

The voltage source inverter is the essential link between a hybrid energy system and the grid. A power quality control scheme is employed to regulate the inverter output for a variety of wind speeds and load fluctuations. Simulation testing demonstrates that the controller associated with the UC is able to quickly compensate for decreases in wind power or changes in the inverter's output. The system is able to utilize the wind power to charge the ultra-capacitor effectively and provide consistent output when needed. All components work together to guarantee a reliable, eco-friendly and controllable energy supply. This hybrid system drastically improves the efficiency and stability of green energy generation when used efficiently.

II. HYBRID SYSTEM

Figure 1 illustrates the schematic block diagram of a hybrid system, which is composed of a Solid Oxide Fuel Cell (SOFC), Wind Energy Conversion System, and an Ultra-Capacitor (UC). To connect SOFC to the common dc-link, a boost converter is used while a combination of a boost converter and diode rectifier is used to connect the wind system to the dc-link. On the other hand, UC is joined to the dc-link through a bidirectional converter. All these components combined yields a hybrid system that is intended to provide efficient energy conversion. The SOFC serves to convert the chemical energy of a fuel to electrical energy, while the wind energy conversion system can do the same by directly converting.

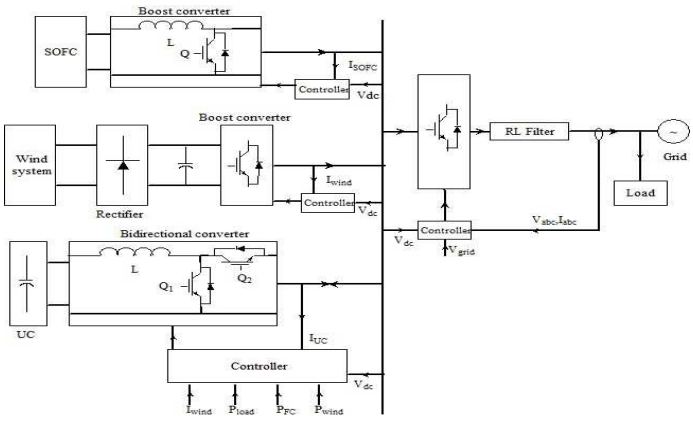

Fig. 1. Schematic of Hybrid system

A. *Solid Oxide Fuel cell*

A Solid Oxide Fuel Cell (SOFC) is a type of electrochemical energy conversion device that is increasingly being utilized as a way to generate electrical energy. This device uses the chemical energy stored in hydrogen fuel and provides electricity, heat and water as byproducts. As compared to other fuel cells, SOFCs are more efficient, versatile and able to produce higher power outputs. The construction of a SOFC is made up of two electrodes that are separated by an electrolyte - the anode side of the cell feeds in hydrogen fuel, while the cathode side requires oxygen as an oxidant. The result of this arrangement is a small voltage output from a single cell to get the required power output, multiple cells

$$V_{stack} = nE - V_{act} - V_{con} - V_{ohmic} \qquad (1)$$

Where V_{stack}= stack voltage, n= number of cells,E=Nerst reversible voltage, V_{act}= activation voltage loss, V_{con}= concentration loss, V_{ohmic}= ohmic loss.

Considering the partial pressure of hydrogen and oxygen which are reactants and water as exhaust. The SOFC voltage is given by Nerst equation as given below [10] .

$$E = N_0 + \left[E_0 + \frac{RT}{2F} log\left[\frac{P_{H_2} P_O^{1/2}}{P_{H_2}O}\right]\right] - rI(2)$$

Where

The electric current of the fuel cell stack can be calculated by combining the open cell voltage (E0), number of cells (N0) in the stack, universal gas constant (R), temperature (T), Faraday's constant (F), partial pressure of hydrogen (), partial pressure of oxygen (), partial pressure of water (), ohmic losses (r), and output voltage (E).

The amount of pressure exerted by hydrogen on a given environment is specified. [10].

$$P_{H_2} = \frac{1/K_{H_2}}{1 + \tau H_2 s}\left(q_{H_2}^{in} - 2k_r I_{fc}\right)$$

Where

P_{H_2} = Valve molar constant of hydrogen, τH_2 =Hydrogen flow response time, K_r= constant, I_{fc}= Fuel stack current.

This paper utilises a dynamic model based on the one presented in the literature to calculate the partial pressure of oxygen and water. [9].

B. Wind Generation

The power generated by the wind turbine in this paper is of variable speed and directly linked to a Permanent Magnet Synchronous Generator (PMSG). [11].

$$P = 0.5\rho A C_p(\lambda,\beta)V_w^3 \quad (3)$$

Where

P= power (Watts) , ρ= air density, A= swept area by rotor blades, C_p =power coefficient of rotor, λ= tip speed ratio, β= blade pitch angle, V_w= wind speed (m/s).

The tip speed ratio is the ratio between the linear speed of a blade at its tip and the speed of the wind in the surrounding environment. It is calculated by dividing the linear speed of the blade tip by the free stream wind speed.

$$\lambda = \frac{\omega_m R}{V_w} \quad (4)$$

Where R= radius of the rotor, ω_m = rotor speed in rad/sec.

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \quad (5)$$

Where $\lambda_i = \left[\frac{1}{\lambda_i + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]$ (6

The torque produced by the wind turbine is given by

$$T_w = \frac{P}{\omega_m} \quad (7)$$

The present study looks into the use of a Permanent Magnet Synchronous Generator (PMSG) directly coupled with a wind turbine. The parameters for the wind turbine and PMSG have been taken from previous research. [12].

C. Ultracapacitr

The ultra-capacitor is a device which utilizes electrochemical processes to store energy as an electrical charge.. It offers high energy density, low power losses, fast response times and long cycle life, making it a useful alternative to other energy storage devices such as batteries. Its applications are wide ranging and include vehicles, digital cameras, portable electronics and renewable energy systems. Its main drawback is its relatively high cost but this is expected to decrease in the near future with more research and development in the field.[6,13]

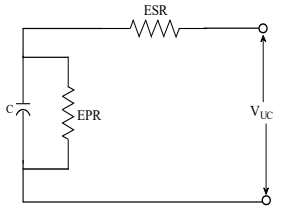

Fig. 2. Schematic of Ultracapcitor model.

The amount of energy that is output from the UC is determined by

$$E_{UC} = \frac{1}{2}C\left(V_i^2 - V_f^2\right) \quad (8)$$

Where E_{UC}=Ultra-capacitor energy, V_i=initial terminal voltage, V_f= final terminal voltage.

In this paper the initial voltage in taken as 380V(V_i) and final voltage as 190V (V_f).The ultra-capacitor parameters are calculated using [13,14].

III. Power Electronic Controller

Power electronics converters are essential to making the most of hybrid DG systems. Boost converters are utilized in order to link two power sources to the same DC-link while a bidirectional converter is used to connect the UC to the same DC-link. It is critical to adjust the control of these converters to make sure they align with the grid parameters. Regulation is necessary to ensure that the energy sources flow together as planned, without problems for the power grid. To do this accurately, it is important to use proper converter controls to properly manage the energy sources and the grid. Power electronic converters are therefore required for an efficient and successful hybrid DG system.

This paper aims to illustrate the implementation of two boost converters connected together to form a common direct current link (DC-link). The reference voltage (Vdcref) is used to maintain the DC-link voltage and compared to ensure the desired output. Then, the error is provided to a Proportional-Integral (PI) controller which produces a reference current. In turn, this reference current is compared to the actual current and the subsequent error is delivered to the PI controller to generate gating signals for the converter switch. The controllers associated with the SOFC and wind are chosen to ensure that the power generated from wind is injected into the dc-link and the remaining demanded power is delivered by the SOFC system. To achieve this, it is assumed that the inverter output is always maintained at a higher or equal level compared to the amount of energy generated by the wind system. This helps to maintain the power balance and constancy in the dc-link voltage.

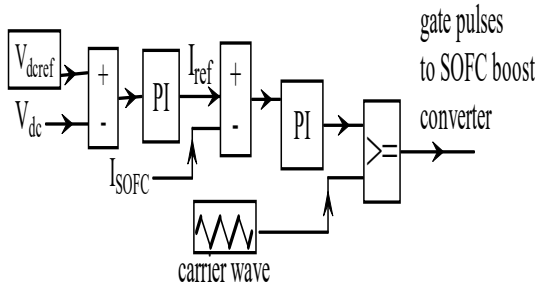

Fig. 3. Schematic of boost converter controller.

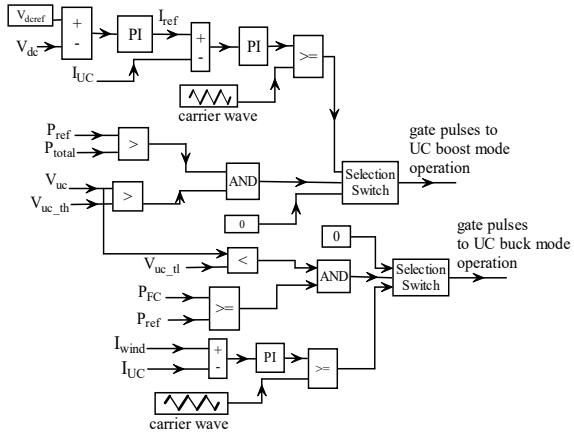

Fig. 4. Schematic of bidirectional converter control.

The schematic of a bidirectional converter controller is shown in Figure 4. This controller functions similarly to those of a solid oxide fuel cell and a wind turbine, with a boost action that takes place when the Pref of the inverter is higher than the combined power output of the SOFC and wind turbine and when the Vuc is above the lower threshold limit (Vuc_th). The parameters are set such that as the SOFC power increases, the UC power decreases. In this situation, the boost converter will be active, transferring any remaining power deficiency.

The buck mode operation of converter controller is carried to charge the UC from wind power shown Figure 4. In order to activate buck mode of operation it is necessary to ensure that UC is not delivering power and wind power is also at minimum generation. This condition is checked in order to avoid the situation when the wind is generating higher power level if charging of UC is activated the sudden deficit in power cannot be compensated, hence affects the inverter output. The buck mode of operation is initiated by checking the status of power of fuel cell (PFC) and inverter power reference (Pref). The UC is charged using wind power. The wind current I wind is compared with ultracapcitor current, the error in given to PI controller to generate the gating signal to buck converter switch.

The diagram of the inverter regulator is represented in the figure 5, which employs a PQ control scheme for the DG system's grid-connected mode. By setting the inverter output power reference, the inverter output can be scheduled. The phase lock loop (PLL) synchronises the inverter with the grid. However, should the grid fail, the control scheme is rendered ineffective due to the absence of a reference voltage.

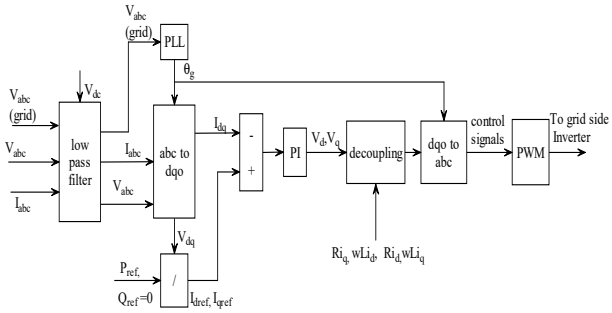

Fig. 5.:Schematic of Inverter Control

To implement the PQ control scheme the ac side parameters are converter into dq frame. The references P and Q(Q=0) set points and grid parameter Vdq are used to calculate the Idref and Iqref. By regulating Id and Iq component the active and reactive power output are regulated. The PI controller are used to regulate the current in dq synchronous frame. The decoupling terms are considered for independent control of id and iq. The controllers in dq frame are given as. [15]

$$u_d = v_d - R_f I_d - L_f \frac{dI_d}{dt} + \omega L_f I_q \quad (9)$$

$$u_q = v_q - R_f I_q - L_f \frac{dI_q}{dt} + \omega L_f I_d \quad (10)$$

IV. RESULTS

The hybrid model is simulated using Matlab/Simulink. The hybrid system is simulated assuming sufficient fuel is available for SOFC operation, inverter output is higher or equal to wind power generated. The inverter supplies only active power and load considered is of resistive. Simulation parameters are given in Table 1.

Table I. Simulation parameters.

Grid Parameters	220V, 60Hz, line filter R=0.2Ω ,L=2mH
dc-link voltage	750V
SOFC Parameters	Rated power = 100kW,No. of cells in series in the stack= 400
PMSG parameters	Rated Power =55-kW, 250-V, 26-Hz, Y-connected, Rs=0.04Ω, Ld=Lq=8.5 mH,Inertia=1.5kg-m^2, No. of poles (P) = 40 , Flux/pole=1.8Wb
Wind turbine parameter	The 55kW rated power generator operates in the wind speed range of 6-12m/s, with a rotor speed of 28.94–79.3 RPM and an inertia of 13.5 kg-m2. It has a radius of 7.5m and a maximum coefficient of power of 0.4412, and a tip speed ratio of 5.66.
Ultra-capacitor Parameters	Rated power= 100kW, Capacitance=125F, No. of UC in series=6, No of UC in parallel=8 (BMOD0094 P075 B02,94F, 75 V, ESR=13mΩ)

The behaviour of a Solid Oxide Fuel Cell (SOFC) when the load changes without using an ultra-capacitor is demonstrated in Figure 6. The inverter reference is changed from 10kW to 90kW at time 2s and it can be observed that the power outputted by the SOFC takes some time to arrive at the desired level. To meet the required power requirements, the grid is used to supply the load in the interim. As seen in Figure 7, the slow reaction of the SOFC impacts the dc-link voltage and consequently, the power outputted from the inverter. The figure illustrates how the voltage varies due to the lack of immediate response from the SOFC.

The SOFC's response time is quite long, as seen in Figure 6. It is evident that the SOFC requires considerable time to reach the desired power output, causing a delay in the inverter's output. This can be a major issue when the load needs to be changed frequently, since theSOFC's response time could cause the load to remain without the desired power supply for a certain period.

This is the reason why the use of an ultra-capacitor is often recommended when using a SOFC. An ultra-capacitor can respond quickly to changes in power demand, thus providing an additional layer of protection against sudden surges in power requirement. Adding an ultra-capacitor to the system can help compensate for the SOFC's slower response time, ensuring a stable and reliable power supply to the load.

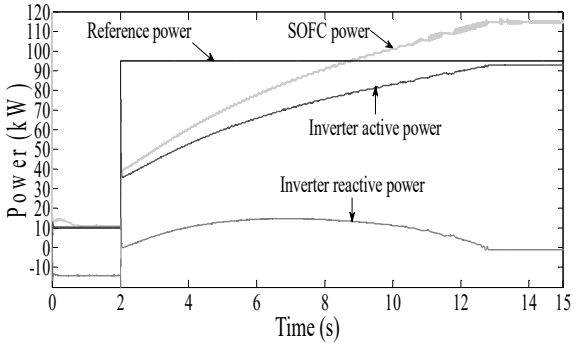

Fig. 6. Power variation without ultra-capacitor.

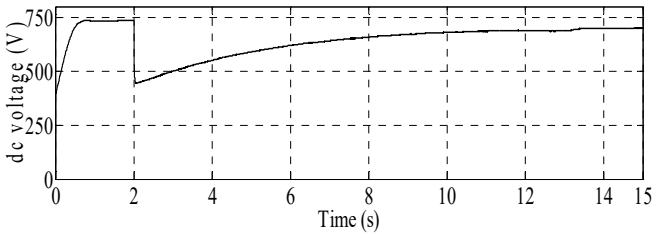

Fig.7. dc-link voltage without ultra-capacitor.

The Figure 7. Shows the dc-link voltage variation for change in SOFC power production. From the Figures 7 and 8 it is clear that the SOFC system requires a compensating system for change in the SOFC power generation.

The Figure 8. Shows the power variation at dc-link with ultra-capacitor for change in inverter output power. Initially the power reference is kept at 10kW and it increased to 30kW, 60kW and 90kW at time intervals of 2, 4 and 6s respectively. For every change in inverter power output the ultra- capacitor system acts instantly and compensates the deficit power. As the power increases the UC power decreases. During this time the wind system do not contribute any power as the wind speed is maintained at minimum (1m/s) level.

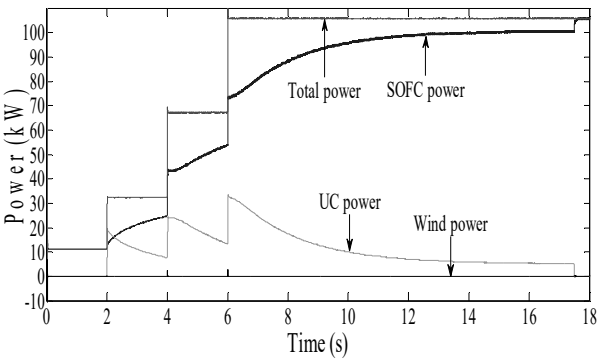

Fig.8. power variation at dc link

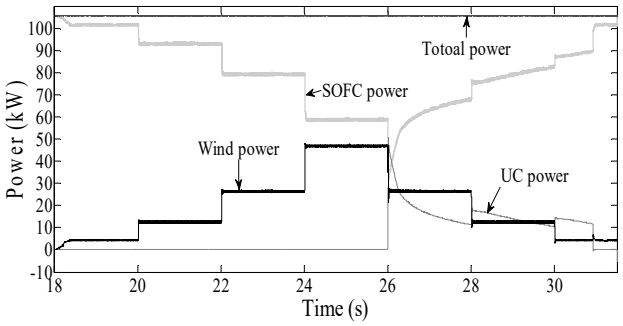

Fig. 9. power variation at dc-link with change in wind speed

The Wind System and Solid Oxide Fuel Cell (SOFC) are used together to continuously generate the necessary electricity for a system. At 18 seconds, the wind speed is 6 meters per second and the SOFC is providing most of the power required. As the wind picks up, the power provided by the SOFC decreases; at 20, 22 and 24 seconds, the wind speed increases to 8, 10 and 12 m/s respectively and the SOFC output correspondingly reduces. When the wind drops back to 10 m/s at 26s, the Uninterruptible Controller (UC) is triggered to supply any power that may be missing to ensure that the total power remains the same. As the SOFC output begins to rise, the UC will begin to reduce its own output. At 28s and 30s, when the wind speed falls again to 8 and 6 m/s respectively, the UC will chip in and make up for the power deficit. This coordination between the Wind System and the SOFC allows them to share the load, so that the total power requirement is always met.

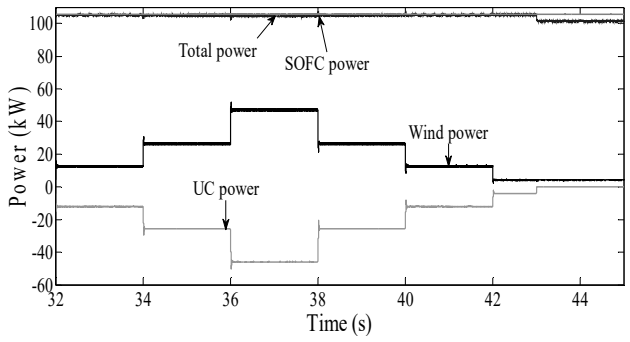

Fig. 10. Charging of ultra-capacitor voltage and harmonic contents

The charging of an ultra-capacitor (UC) using wind power is shown in Figure 10. The wind speed varies from 6 to 12 m/s in 2 m/s increments at 2s intervals. Accordingly, the UC charging varies based on the generated wind power. The controller is set to ensure that the SOFC power stays constant and the inverter output is kept constant during charging.

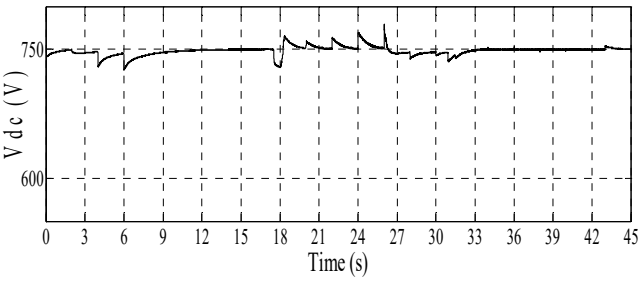

Fig. 11. dc-link voltage.

The Figure 11. shows the dc-link voltage. At time 2, 4 and 6s the dc voltage is dropped due to change in the inverter output. However the dc-link voltage comes back to normal level quickly as the UC stars delivering power and maintains the dc-link voltage to required level. The time interval between 18 to 26s as wind power supply increased which affects the dc-link voltage as seen in the figure. As the controllers acts fast and effectively the dc-link voltage maintained constant. A dip in dc voltage can be observed during time intervals of 26, 28, 30s due reduction in the wind power generation.

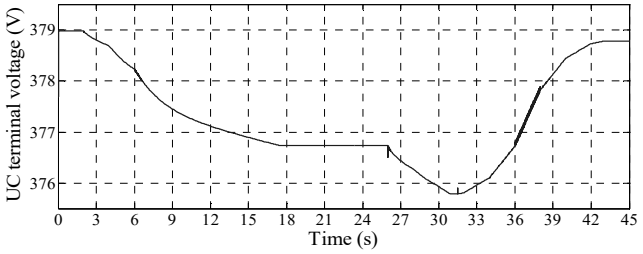

Fig. 12. Ultra-capacitor terminal voltage.

The Figure 12. shows the UC terminal voltage variation. From 0 to 17s the UC capacitor releases the power to dc-link to compensate the deficit power, its terminal voltage drops gradually. Once the UC stops discharging the terminal voltage becomes constant during the time period of 17 to 26s. From time 26s to 32s UC terminal voltage further decreases as the wind power generation reduced during the time interval. From 32s to 43s the ultra-capacitor is charged using wind power. As UC charges the terminal voltage increases as seen in the figure. During the simulation, the wind speed fluctuated between 1 m/s and 12 m/s. From 0 to 18s, the wind speed stayed at a minimum of 1m/s. After that, it increased by 2 m/s increments until it reached a maximum of 12 m/s.

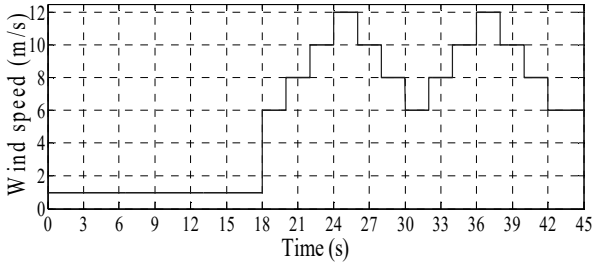

Fig. 13. Wind speed variation

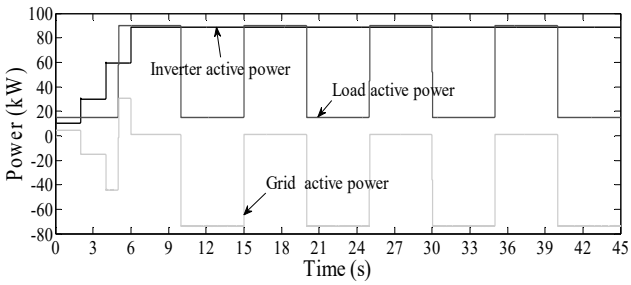

Fig. 14. Active power variation of inverter, load and grid.

Figure 14 displays the active power of the inverter, load and grid. Initially, the inverter active power reference is at 10kW and the load at 15kW. With this, 10kW is supplied by the inverter and 5kW by the grid. At 2 seconds, the inverter power reference increased to 30kW, with 15kW being provided by the grid. As the inverter output power was raised to 60kW and 90kW at 4 and 6 seconds respectively, more energy was sent to the grid. The resistive load of 15kW was connected every 0-5s, 10-15s, 20-25s, 30-35s and 40-45s intervals. Moreover, the 90kW load was considered between the time frames of 5-10s, 15-20s, 25-30s and 35-40s. With such varying loads, the inverter still managed to provide a steady, consistent power supply to both the load and grid.

The Figure 15. shows the rms voltage at common coupling point. For change in the load or inverter output the voltage remains constant.

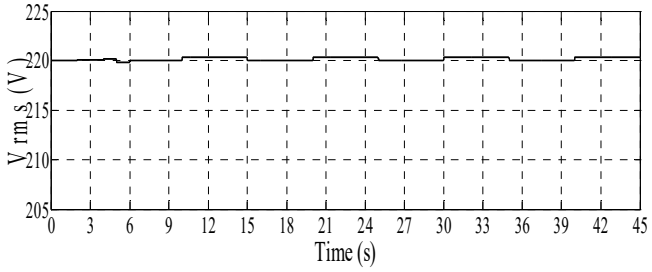

Fig. 15. rms voltage of common coupling point.

V. CONCLUSIONS

The Solid Oxide Fuel Cell (SOFC) is a dispatchable power source, meaning its output can be scheduled. Unfortunately, SOFC has a slow dynamic response to load changes, so short-term compensation is needed during the transient period. Ultra-capacitors have high power density, so they can be used to counterbalance the slow dynamics of SOFC. This paper presents a solid oxide fuel cell and wind based hybrid system with ultra-capacitor and its performance. Fluctuating power generated from wind systems is effectively compensated for by combining solid oxide fuel cells and ultra-capacitors. The control schemes employed manage power production and sharing between the wind and SOFC units. Ultra-capacitors instaneously supplement any deficit during transient periods. Power output from the hybrid system is no longer limited by wind availability. The wind power is used to charge the ultra-capacitor, making the hybrid system more eco-friendly. The hybrid system is still dispatchable even in varying wind speeds.

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