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A Novel Power Converter for Energy Management in Photovoltaic/Battery/Wind Hybrid Distributed Generation System

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ABSTRACT

This study introduces an innovative power converter designed to enhance energy management in a hybrid distributed generation system comprising photovoltaic (PV), battery storage, and wind energy components. Utilizing MATLAB for detailed simulation and analysis, the proposed converter architecture aims to optimize the integration and utilization of renewable energy sources, ensuring efficient energy conversion and stable power supply. The converter's unique control strategies and topology enable effective handling of the variability inherent in solar and wind energy, thereby improving system reliability and performance. Simulation results underscore the converter's capability to achieve higher energy conversion efficiency and operational flexibility compared to existing technologies. This research marks a significant step towards sustainable energy management, offering a scalable solution for integrating diverse renewable energy sources into the grid.

KEYWORDS: Distributed Generation System, Photovoltaic, Battery Energy Storage, Power Converter, Energy Management, MATLAB/Simulink, Renewable Energy.

1. INTRODUCTION

Electric utilities and end users of electric power are becoming increasingly concerned about meeting the growing energy demand. Seventy five percent of total global energy demand is supplied by the burning of fossil fuels. But increasing air pollution, global warming concerns, diminishing fossil fuels and their increasing cost have made it necessary to look towards renewable sources as a future energy solution. Since the past decade, there has been an enormous interest in many countries on renewable energy for power generation. The market liberalization and government's incentives have further accelerated the renewable energy sector growth.

Renewable energy source (RES) integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ)issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network.

2. DISTRIBUTED ENERGY SYSTEMS:

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation resources around the world. As shown in Fig.1 the currently competitive small generation units and the incentive laws to use renewable energies force electric utility companies to construct an increasing number of distributed generation units on its distribution network, instead of large central power plants. Moreover, DES can offer improved service reliability, better economics and a reduced dependence on the local utility. Distributed Generation Systems have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generation as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anythingexcept for an emergency basis.

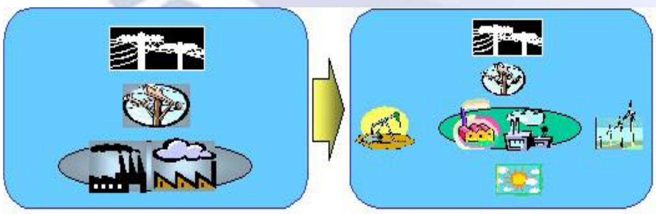

Fig 1. A large central power plant and distributed energy systems

Meanwhile, recently, the use of Distributed Energy Systems under the 500 kW level is rapidly increasing due to recent technology improvements in small generators, power electronics, and energy storage devices. Efficient clean fossil fuels technologies such as micro-turbines and fuel cells, and environmentally friendly renewable energy technologies such as solar/photovoltaic's, small wind and hydro are increasingly used for new distributed generation systems.

These DES are applied to a standalone, a standby, a grid-interconnected, a cogeneration, peak shavings, etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc.

The major Distributed Generation technologies that will be discussed in this section are as follows: micro-turbines, fuel cells, solar/photovoltaic systems, and energy storage devices.

Micro-turbines, especially the small gas fired micro turbines in the 25-100 kW that can be mass-produced at low cost have been more attractive due to the competitive price of natural gas, low installation and maintenance costs. It takes very clever engineering and use of innovative design (e.g. air bearing, recuperation) to achieve reasonable efficiency and costs in machines of lower output, and a big advantage of these systems is small because these mainly use high-speed turbines (50,000-90,000 RPM) with air foil bearings. Therefore, micro turbines hold the most promise of any of the DES technologies today.

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or produced from natural gas, or liquid fuels such as alcohols, or gasoline. Each unit ranges in size from 3 – 250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid cell are commercially available in the range of the 200 kW, while solid oxide and molten carbonate cell are in a pre-commercial stage of development.

The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon.Mixed micro-turbine and fuel cell systems will also be available as a distributed generation source.Recently, a solid oxide fuel cell has been combined with a gas micro-turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 %, and the expected power levels range from 250 kW to 2.5 MW. Solar/photovoltaic systems may be used in a variety ofsizes, but the installation of large numbers of photovoltaic systems is undesirable due to high land costs and in many geographic areas with poor intensity and reliability of sunlight.

In general, almost one acre of land would be needed to provide 150 kW of electricity, so solar/photovoltaic systems will continue to have limited applications in the future.

Energy storage devices such as ultra capacitors, batteries, and flywheels are one of the most critical technologies for DES. In general, the electrochemical capacitor has high power density as well as good energy density.

In particular, ultra capacitors have several benefits such as high pulse powercapacity, long lifetime, high power density, low ESR, and very thin and tight. In contrast, batteries have higher energy density, but lower power density and short lifetime relative to ultra-capacitor. So hybrid Power System, a combination of ultra-capacitor and battery, is strongly recommended to satisfy several requirements and to optimize system performance. Recently storage systems are much more efficient, cheaper, and longer than five years ago. In particular, flywheel systems can generate 700 kW for 5 seconds, while 28-cell ultra capacitors can provide up to 12.5 kW for a few seconds.

In the past, the electric utility industry did not offer various options that were suited for a wide range of consumer needs, and most utilities offered at best two or three combinations of reliability-price. However, the types of modern DES give commercial electric consumers various options in a wider range of reliability-price combinations. For these reasons, DES will be very likely to thrive in the next 20 years, and especially, distributed generation technologies will have a much greater market potential in areas with high electricity costs and low reliability such as in developing countries.

Configurations for DES

Case I: A Power Converter connected in a Standalone AC System or in Parallel with the Utility Mains

Fig.2 show a distributed power system which is connected to directly load or in parallel with utility mains, according to its mode. This system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, output sensor (V, I, P), and a DSP controller. In the Figures a distributed generator may operate as one of three modes:as in fig.2 standby, fig.3a peak shaving, and fig.4 a standalone power source. In a standby mode shown in figures a generator set serves as a UPS system operating during mains failures. It is used to increase the reliability of the energy supply and to enhance the overall performance of the system.

The static switch SW 1 is closed in normal operation and SW 2 is open, while in case of mains failures or excessive voltage drop detection SW 1 is open and SW 2 is simultaneously closed. In this case, control techniques of DES are very similar to those of UPS. If a transient load increases, the output voltage has relatively large drops due to the internal impedance of the inverter and filterstage, which frequently result in malfunction of sensitive load. Fig.4 can serves as a peak shaving or interconnection with the grid to feed power back to mains.

In both modes, the generator is connected in parallel with the main grids. In a peak shaving mode, this generator is running as few as several hundred hours annually because the SW 1 is only closed during the limited periods. Meanwhile, in an interconnection with the grid, SW 1 is always closed and this system provides the grid with continuous electric power. In addition, the converter connected in parallel to the mains can serve also as a source of reactive power and higher harmonic current components.

In a standalone AC system shown in Fig. the generator is directly connected to the load lines without being connected to the mains and it will operate independently. In this case, the operations of this system are similar to a standby mode, and it serves continuously unlike a standby mode and a peak shaving mode.

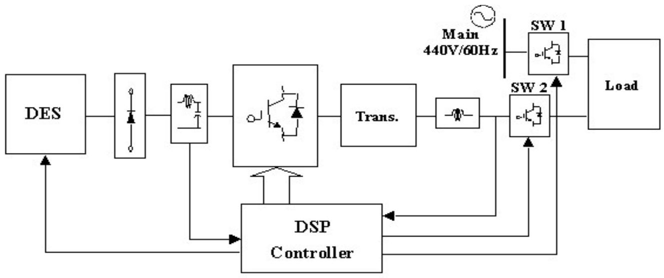

Fig.2 Block diagram of a standby mode

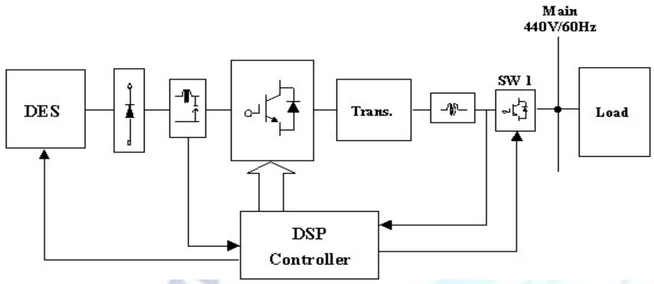

Fig.3 Block diagram of a peak shaving mode

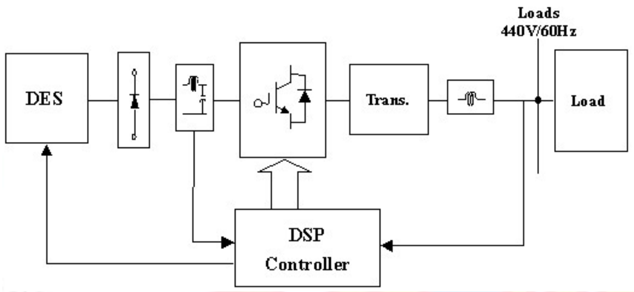

Fig.4 Block diagram of a standalone mode

3. POWER MANAGEMENT SYSTEM:

CONTROL OF THE HYBRID SYSTEM

The control modes in the microgrid include unit power control, feeder flow control, and mixed control mode. The two control modes were first proposed by Lasserter. In the UPC mode, the DGs (the hybrid source in this system) regulate the voltage magnitude at the connection point and the power that source is injecting. In this mode if a load increases anywhere in the microgrid, the extra power comes from the grid, since the hybrid source regulates to a constant power. In the FFC mode, the DGs regulate the voltage magnitude at the connection point and the power that is flowing in the feeder at connection point. With this control mode, extra load demands are picked up by the DGs, which maintain a constant load from the utility viewpoint.

In the mixed control mode, the same DG could control either its output power or the feeder flow power. In other words, the mixed control mode is a coordination of the UPC mode and the FFC mode. Both of these concepts were considered. In this paper, a coordination of the UPC mode and the FFC mode was investigated to determine when each of the two control modes was applied and to determine a reference value for each mode. Moreover, in the hybrid system, the PV and PEMFC sources have their constraints. Therefore, the reference power must be set at an appropriate value so that the constraints of these sources are satisfied.

The proposed operation strategy presented in the next section is also based on the minimization of mode change. This proposed operating strategy will be able to improve performance of the system's operation and enhance system stability.

OPERATING STRATEGY OF THE HYBRID SYSTEM

As mentioned before, the purpose of the operating algorithm is to determine the control mode of the hybrid source and the reference value for each control mode so that the PV is able to work at maximum output power and the constraints $(P_{FC}^{low}, P_{FC}^{up}, \text{ and } P_{F}^{max})$ are fulfilled.

Once the constraints (and) are known, the control mode of the hybrid source (UPC mode and FFC mode) depends on load variations and the PV output. The control mode is decided by the algorithm shown in Fig. 7, Subsection B. In the UPC mode, the reference output power of the hybrid source depends on the PV output and the constraints of the FC output. The algorithm determining is presented in Subsection A and is depicted in Fig. 4.

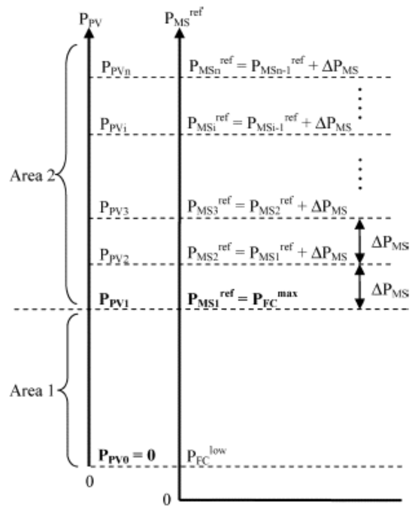

Fig. 4. Operation strategy of hybrid source in the UPC mode.

Operating Strategy for the Hybrid System in the UPC Mode

In this subsection, the presented algorithm determines the hybrid source works in the UPC mode. This algorithm allows the PV to work at its maximum power point, and the FC to work within its high efficiency band. In the UPC mode, the hybrid source $P_{\rm MS}^{\rm ref}$ regulates the output to the reference value. Then

$$P_{\rm PV} + P_{\rm FC} = P_{\rm MS}^{\rm ref}. \qquad (11)$$

Equation (11) shows that the variations of the PV output will be compensated for by the FC power and, thus, the total power will be regulated to the reference value.

However, the FC output must satisfy its constraints and, hence, $P_{\rm MS}^{\rm ref}$ must set at an appropriate value. Fig. 4 shows the operation strategy of the hybrid source in UPC mode to determine $P_{\rm MS}^{\rm ref}$. The algorithm includes two areas: Area 1 and Area 2.

In Area 1, $P_{\rm PV}$ is less than $P_{\rm PV1}$, and then the reference Power $P_{\rm MS1}^{\rm ref}$ is set at $P_{\rm FC}^{\rm up}$ where

$$P_{\rm PV1} = P_{\rm FC}^{\rm up} - P_{\rm FC}^{\rm low} \qquad (12)$$
$$P_{\rm MS1}^{\rm ref} = P_{\rm FC}^{\rm up}. \qquad (13)$$

If PV output is zero, then (11) $P_{\rm FC}$ deduces to be equal to $P_{\rm FC}^{\rm up}$. If the PV output increases to $P_{\rm PV1}$, then from (11) and (12), we obtain $P_{\rm FC}$ equal to $P_{\rm FC}^{\rm low}$. In other words, when the PV output varies from zero to $P_{\rm PV1}$, the FC output will change from $P_{\rm FC}^{\rm up}$ to $P_{\rm FC}^{\rm low}$. As a result, the constraints for the FC output always reach Area 1. It is noted that the reference power of the hybrid source during the UPC mode is fixed at a constant $P_{\rm FC}^{\rm up}$. Area 2 is for the case in which PV output power is greater Than $P_{\rm PV1}$. As examined earlier, when the PV output increases. To $P_{\rm PV1}$, the FC output will decrease to its lower limit $P_{\rm FC}^{\rm low}$. If PV output keeps increasing, the FC output will decrease below its limit $P_{\rm FC}^{\rm low}$.

In this case, to operate the PV at its maximum power point and the FC within its limit, the reference power must be increased. As depicted in Fig. 4, if PV output is larger than $P_{\rm PV1}$, the reference power will be increased by the amount of $\Delta P_{\rm MS}$, and we obtain

$$P_{\rm MS2}^{\rm ref} = P_{\rm MS1}^{\rm ref} + \Delta P_{\rm MS}. \qquad (14)$$

Similarly, if $P_{\rm PV}$ is greater than $P_{\rm PV2}$, the FC output becomes less than its lower limit and the reference power will be thus increased by the amount of $\Delta P_{\rm MS}$. In other words, the reference

power remains unchanged and equal to $P_{\rm MS2}^{\rm ref}$ if is less than $P_{\rm PV2}$ and greater than $P_{\rm PV1}$.
where

$$P_{\rm PV2} = P_{\rm PV1} + \Delta P_{\rm MS} \qquad (15)$$

it is noted that $\Delta P_{\rm MS}$ is limited so that with the new reference power, the FC output must be less than its upper limit $P_{\rm FC}^{\rm up}$. Then, we have

$$\Delta P_{\rm MS} \le P_{\rm FC}^{\rm up} - P_{\rm FC}^{\rm low}. \qquad (16)$$

In general, if the PV output is between
$P_{\rm PVi}$ and $P_{{\rm PV}i-1}$ and , then we have

$$P_{{\rm MS}i}^{\rm ref} = P_{{\rm MS}i-1}^{\rm ref} + \Delta P_{\rm MS} \qquad (17)$$
$$P_{{\rm PV}i} = P_{{\rm PV}i-1} + \Delta P_{\rm MS}. \qquad (18)$$

Equations (17) and (18) show the method of finding the reference power when the PV output is in Area 2. The relationship between $P_{{\rm MS}i}^{\rm ref}$ and $P_{{\rm PV}i}$ is obtained by using (12), (13), and
(18) in (17), and then

$$P_{{\rm MS}i}^{\rm ref} = P_{{\rm PV}i} + P_{\rm FC}^{\rm min}, \quad i = 2, 3, 4 \ldots \qquad (19)$$

The determination of $P_{\rm MS}^{\rm ref}$ in Area 1 and Area 2 can be generalized by starting the index from 1. Therefore, if the PV output

$$P_{{\rm PV}i-1} \le P_{\rm PV} \le P_{{\rm PV}i}, \quad i = 1, 2, 3 \ldots$$

then we have

$$P_{{\rm MS}i}^{\rm ref} = P_{{\rm PV}i} + P_{\rm FC}^{\rm min}, \quad i = 1, 2, 3 \ldots \qquad (20)$$
$$P_{{\rm PV}i} = P_{{\rm PV}i-1} + \Delta P_{\rm MS}, \quad i = 2, 3, 4 \ldots \qquad (21)$$

it is noted that $i = 1, P_{\rm PV1}$ when is given in (12), and

$$P_{{\rm PV}i-1} = P_{\rm PV0} = 0. \qquad (22)$$

In brief, the reference power of the hybrid source is determined according to the PV output power. If the PV output is in Area 1, the reference power will always be constant and set at $P_{\rm FC}^{\rm up}$. Otherwise, the reference value will be changed by the amount of ΔP_{MS}, according to the change of PV power.

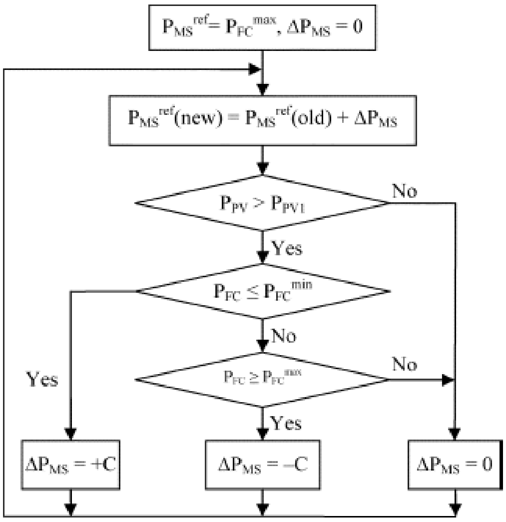

Fig. 5. Control algorithm diagram in the UPC mode (P_{MS}^{ref} automatically changing).

The reference power of the hybrid source in Area 1 and Area 2 is determined by (20) and (21). , and are shown in (22), (12), and (16), respectively. Fig. 5. shows the control algorithm diagram for determining the reference power automatically. The constant must satisfy (16). If increases the number of change of will decrease and thus the performance of system operation will be improved.

However, C should be small enough so that the frequency does not change over its limits 5%). In order to improve the performance of the algorithm, a hysteresis is included in the simulation model. The hysteresis is used to prevent oscillation of the setting value of the hybrid system reference power . At the boundary of change in , the reference value will be changed continuously due to the oscillations in PV maximum power tracking. To avoid the oscillations around the boundary, a hysteresis is included and its control scheme to control is depicted in Fig.6.

B. Overall Operating Strategy for the Grid-Connected Hybrid System

It is well known that in the microgrid, each DG as well as the hybrid source has two control modes: 1) the UPC mode and 2) the FFC mode.

In the aforementioned subsection, a method to determine in the UPC mode is proposed. In this subsection, an operating strategy is presented to coordinate the two control modes.

The purpose of the algorithm is to decide when each control mode is applied and to determine the reference value of the feeder flow when the FFC mode is used. This operating strategy must enable the PV to work at its maximum power point, FC output, and feeder flow to satisfy their constraints. If the hybrid source works in the UPC mode, the hybrid output is regulated to a reference value and the variations in load are matched by feeder power. With the reference power proposed in Subsection A, the constraints of FC and PV are always satisfied. Therefore, only the constraint of feeder flow is considered. On the other hand, when the hybrid works in the FFC mode, the feeder flow is controlled to a reference value

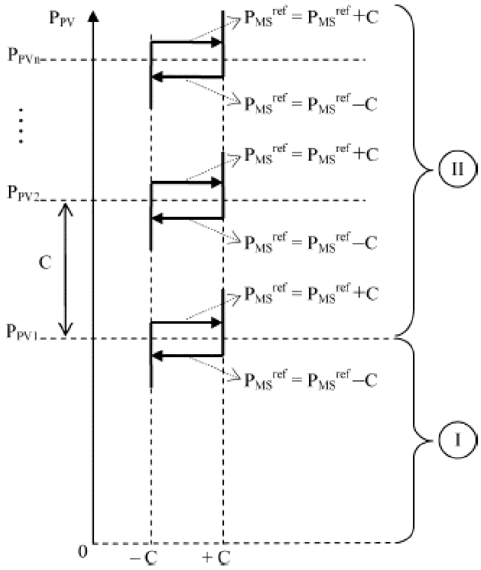

Fig. 6. Hysteresis control scheme for P_{MS}^{ref} control.

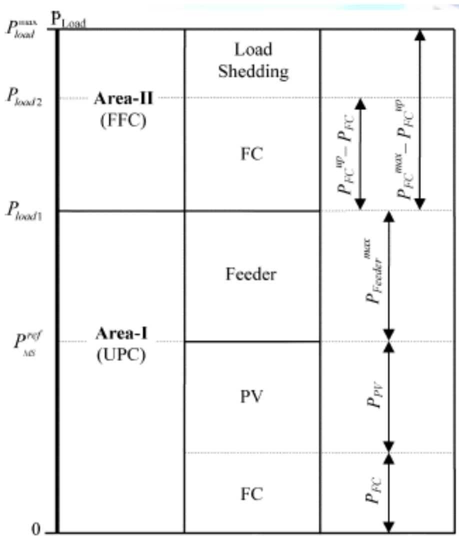

Fig. 7. Overall operating strategy for the grid-connected hybrid system.

And, thus, the hybrid source will compensate for the load variations. In this case, all constraints must be considered in the operating algorithm. Based on those analyses, the operating strategy of the system is proposed as demonstrated in Fig. 7. The operation algorithm in Fig. 7 involves two areas (Area I and Area II) and the control mode depends on the load power. If load is in Area I, the UPC mode is selected. Otherwise, the FFC mode is applied with respect to Area II. In the UPC area, the hybrid source output.

If the load is lower than , the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand. When load increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum , then the feeder flow cannot meet load demand if the load keeps increasing. In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area II is

$$P_{\mathrm{Load1}} = P_{\mathrm{Feeder}}^{\mathrm{max}} + P_{\mathrm{MS}}^{\mathrm{ref}}. \quad (23)$$

When the mode changes to FFC, the feeder flow reference must be determined. In order for the system operation to be seamless, the feeder flow should be unchanged during control mode transition. Accordingly, when the feeder flow reference is set at , then we have

$$P_{\mathrm{Feeder}}^{\mathrm{ref}} = P_{\mathrm{Feeder}}^{\mathrm{max}}. \quad (24)$$

In the FFC area, the variation in load is matched by the hybrid source. In other words, the changes in load and PV output are compensated for by PEMFC power. If the FC output increases to its upper limit and the load is higher than the total generating power, then load shedding will occur. The limit that load shedding will be reached is

$$P_{\mathrm{Load2}} = P_{\mathrm{FC}}^{\mathrm{up}} + P_{\mathrm{Feeder}}^{\mathrm{max}} + P_{\mathrm{PV}}. \quad (25)$$

Equation (25) shows that is minimal when PV output is at 0 kW. Then

$$P_{\mathrm{Load2}}^{\mathrm{min}} = P_{\mathrm{FC}}^{\mathrm{up}} + P_{\mathrm{Feeder}}^{\mathrm{max}}. \quad (26)$$

Equation (26) means that if load demand is less than , load shedding will never occur.

From the beginning, FC has always worked in the high efficiency band and FC output has been less than . If the load is less than , load shedding is ensured not to occur. However, in severe conditions, FC should mobilize its availability, to supply the load. Thus, the load can be higher and the largest load is

$$P_{\mathrm{Load}}^{\mathrm{max}} = P_{\mathrm{FC}}^{\mathrm{max}} + P_{\mathrm{Feeder}}^{\mathrm{max}}. \quad (27)$$

If FC power and load demand satisfy (27), load shedding will never occur. Accordingly, based on load forecast, the installed power of FC can be determined by following (27) to avoid load shedding. Corresponding to the FC installed power, the width of Area II is calculated as follows:

$$P_{\mathrm{Area-II}} = P_{\mathrm{FC}}^{\mathrm{max}} - P_{\mathrm{FC}}^{\mathrm{up}}. \quad (28)$$

In order for the system to work more stably, the number of mode changes should be decreased. As seen in Fig. 7, the limit changing the mode from UPC to FFC is , which is calculated in (23). Equation (23) shows that depends on $P_{\mathrm{Feeder}}^{\mathrm{max}}$ and $P_{\mathrm{MS}}^{\mathrm{ref}}$. $P_{\mathrm{Feeder}}^{\mathrm{max}}$ is a constant.

Thus depends on Fig. 4 shows that in Area 2 $P_{\mathrm{MS}}^{\mathrm{ref}}$ depends on . Therefore, to decrease the number of mode changes, $P_{\mathrm{MS}}^{\mathrm{ref}}$ changes must be reduced. Thus, ΔP_{MS} must be increased. However

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Unit
P_{FC}^{low}	0.01	MW
P_{FC}^{up}	0.07	MW
P_{Feeder}^{max}	0.01	MW
ΔP_{MS}	0.03	MW

ΔP_{MS} must satisfy condition (16) and, thus, the minimized number of mode change is reached when ΔP_{MS} is maximized

$$\Delta P_{\mathrm{MS}}^{\mathrm{max}} = P_{\mathrm{FC}}^{\mathrm{up}} - P_{\mathrm{FC}}^{\mathrm{low}}. \quad (29)$$

In summary, in a light-load condition, the hybrid source works in UPC mode, the hybrid source regulates output power to the reference value $P_{\mathrm{MS}}^{\mathrm{ref}}$, and the main grid compensates for

load variations. $P_{\mathrm{MS}}^{\mathrm{ref}}$ is determined by the algorithm shown in Fig. 4 and, thus, the PV always works at its maximum power point and the PEMFC always works within the high efficiency

band $(P_{\mathrm{FC}}^{\mathrm{low}} \div P_{\mathrm{FC}}^{\mathrm{up}})$. In heavy load conditions, the control mode changes to FFC, and the variation of load will be matched by the hybrid source. In this mode, PV still works with the MPPT control, and PEMFC operates within its efficiency band until load increases to a very high point. Hence, FC only works outside the high efficiency band $(P_{FC}^{up} \div P_{FC}^{max})$ in severe conditions. With an installed power of FC and load demand satisfying (27), load shedding will not occur. Besides, to reduce the number of mode changes, must be increased and, hence, the number of mode changes is minimized when is maximized, as shown in (29). In addition, in order for system operation to be seamless, the reference value of feeder flow must be set at P_{Feeder}^{max}.

4. MATLAB DESIGN OF CASE STUDY AND RESULTS:

Case I: Fig. 8a

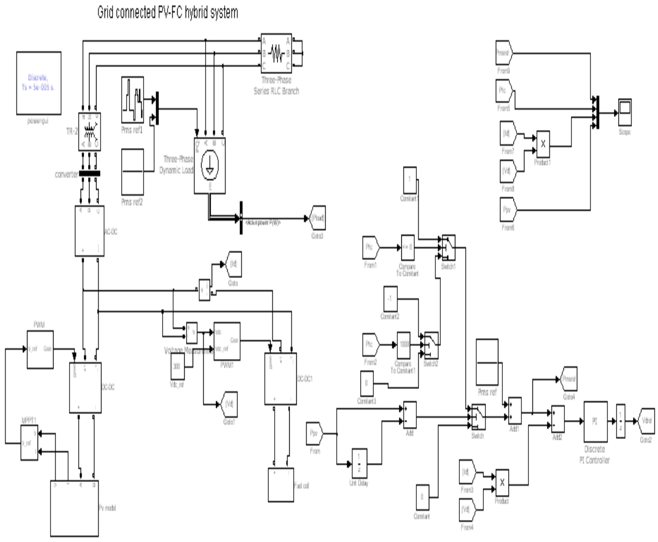

Fig. Grid connected PV-Battery Wind hybrid system

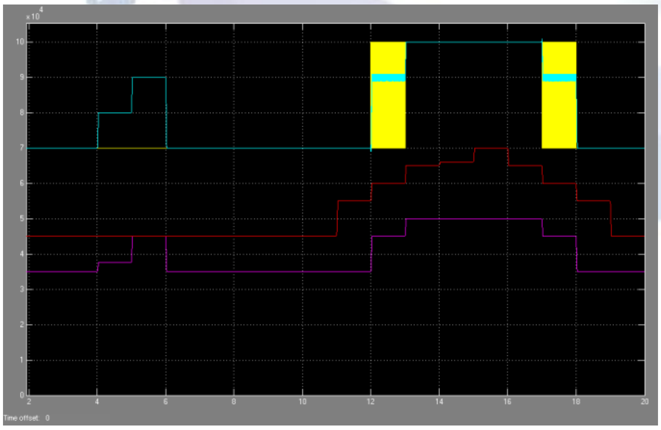

Fig. Operating strategy of the hybridsource.

Case II: Fig. 8b

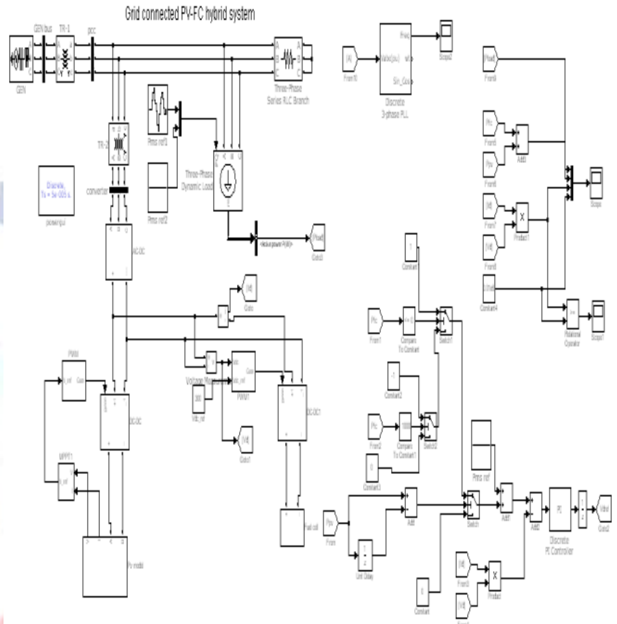

Fig. Grid connected PV-Wind Battery hybrid system

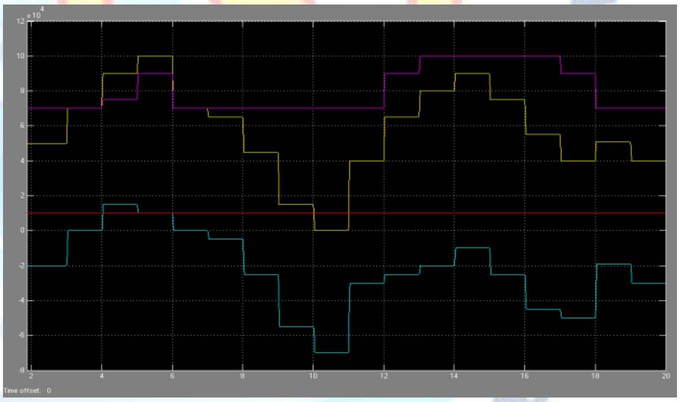

Fig. Operating strategy of the whole system.

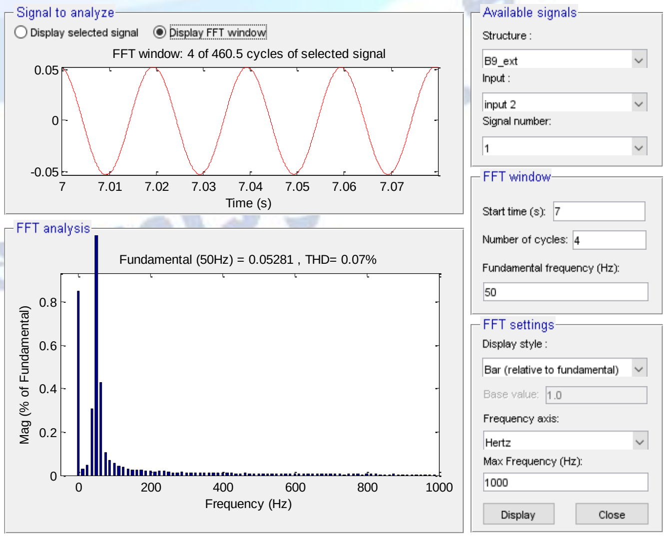

Fig. THD at Grid.

5. CONCLUSIONS:

The proposed power converter demonstrates significant improvements in efficiency when compared to conventional converters. By efficiently managing energy flow within the photovoltaic/battery/wind hybrid distributed generation system, it maximizes energy utilization and minimizes losses.One of the key advantages of the novel power converter is its ability to seamlessly integrate multiple renewable energy sources, namely photovoltaic, battery, and wind, into a single system. This flexibility ensures optimal utilization of available resources, thereby enhancing the overall system performance. Through advanced control algorithms and modulation techniques, the power converter optimally manages the energy flow among different sources and loads. This ensures stable operation of the hybrid distributed generation system while meeting the energy demand efficiently. The robust design of the power converter enhances the reliability and resilience of the hybrid energy system. By effectively handling fluctuations in renewable energy generation and load variations, it ensures continuous power supply with minimal downtime.The proposed power converter architecture is scalable and adaptable to varying system configurations and operational requirements. This makes it suitable for a wide range of applications, from residential to industrial scale, thereby promoting the widespread adoption of hybrid distributed generation systems.

Future Directions: Further research could focus on enhancing the converter's performance through the integration of advanced control techniques, such as predictive control and machine learning algorithms. Additionally, exploring the potential for grid integration and demand-side management could lead to more comprehensive energy management solutions.

In conclusion, the novel power converter presents a promising solution for efficient energy management in photovoltaic/battery/wind hybrid distributed generation systems. Its enhanced efficiency, flexibility, reliability, and scalability make it a valuable contribution to the field of renewable energy integration and sustainable power generation.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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