Design and analysis of an intelligent controller for wind-solar hybrid energy conversion system

Krishnan Suresh[1], Attuluri Rakada Vijay Babu[2,*], Perumal Mahalingam Venkatesh[1]

1. Department of Electrical and Electronics Engineering, Vignan's Foundation for Science, Technology & Research, Guntur, India

2. RC-RES, Department of Electrical and Electronics Engineering, Vignan's Foundation for Science, Technology & Research, Guntur, India

202vijay@gmail.com

ABSTRACT. The paper mainly focusing on the control of Unidirectional Boost Converter (UBC) by DSPIC controller to maintain the constant wind power and solar input. Proper modes of operations required to maintain effective and efficient utilization of power from both the sides of primary and secondary. Some parameters considerations also required to control the modes of operation in the systematic way. A main controller is employed to control the modes of operation in closed loop structure. The operation of Bi-Directional Converter (BDC) is an important role to transfer power from primary source to load and secondary source to battery by different modes of operation. When the input is getting from primary sources such as wind and solar, the operation will be boost mode and also maintain buck mode whenever the secondary source charging the battery which also controlled by DSPIC controller with Proportional Integral and Derivative (PID) control structure. The modes are depending on some inputs like wind speed (v), solar output (Ir), load condition (1/0) & battery state of charge (SOC). Based on these conditions central level main controller has to control the modes of operations in an intelligent approach. This system of approach is very much helpful for agriculture irrigation and lightings.

RÉSUMÉ. Cet article porte principalement sur le contrôle du convertisseur Boost unidirectionnel (UBC, le sigle d' « Unidirectional Boost Converter » en anglais) par le contrôleur dsPIC afin de maintenir l'énergie éolienne et l'entrée solaire constantes. Des modes de fonctionnement appropriés sont nécessaires pour maintenir une utilisation efficace de l'énergie des deux côtés du primaire et du secondaire. Certains paramètres à prendre en compte sont également nécessaires pour contrôler les modes de fonctionnement de manière systématique. Un contrôleur principal est utilisé pour contrôler les modes de fonctionnement dans une structure en boucle fermée. Le fonctionnement du convertisseur bidirectionnel (BDC, le sigle de « Bi-Directional Converter » en anglais) joue un rôle important dans le transfert de l'énergie d'une source primaire à charge et d'une source secondaire à batterie selon différents modes de fonctionnement. Lorsque l'entrée provient de sources primaires telles que l'énergie *éolienne et solaire, le fonctionnement sera en mode Boost et conservera également le mode Buck chaque fois que la source secondaire charge la batterie, qui est également contrôlée par le contrôleur dsPIC avec une structure de régulateur proportionnel intégral et dérivé (PID). Les modes dépendent de certaines entrées telles que la vitesse du vent (v), la sortie solaire (Ir), les conditions de charge (1/0) et l'état de charge de la batterie (SOC, le sigle de « State of Charge » en anglais). Sur la base de ces conditions, le contrôleur principal au niveau central doit contrôler les modes de fonctionnement de manière intelligente. Ce système d'approche est très utile pour l'irrigation et les éclairages agricoles.*

KEYWORDS: *main controller, speedgoat, dspic, grid, wind and solar.*

MOTS-CLÉS: *controleur principal, speedgoat, dsPIC, réseau, énergie éolienne et solaire.*

DOI:10.3166/JESA.51.225-237

1. Introduction

This system of approaches is to insist the importance of power to the consumer. Power generation from renewable sources may helpful to maintain clean and green environment which are very much helpful to the living things. The existing forms of power generation are not an efficient way in both the sides such as health and wealth. Power generation is also from renewable sources such as wind and solar to avoid global warming and environmental pollution. Power supplying authority cannot able to store power because of some disadvantages such as maintenance complexity and fault identification. But small scale of energy storage is possible in the consumer side. Existing system of energy storage consists of different stages of power conversion with specific controller but converters only operating in closed loop but total system are operated by open loop configuration. The drawbacks of this type of systems are effective less operation, harnessing level of natural like wind and solar power also not an efficient. Consumer side power generation is very much required to meet global power demand and to reduce the burden of power supplying authority. The proposed system overcomes these draws back by means of main controller and operates the system is in closed loop. This closed loop configuration system considered the parameters such as wind speed, solar input battery state of charge and load position. Based on this consideration main control has to operate system is in closed loop by means of control breakers controlled by control algorithm. Solar power is only available source, wind power is not available because wind speed $v = 0$ m/s the system operates in mode-1. Solar power is not available source; wind power is only available because wind speed $v > 5$ m/s then the system operates in mode-2. If both powers are available, then battery gets charging from both the sources. In all the three modes battery state of charge is less than 40 %, battery gets charging from solar power by enabling control breaker 1 from main controller and DC load also getting source from the available natural sources. If AC load position is '1' load getting power from grid, then the system import power from grid otherwise it continuing with standalone mode until the above conditions gets false. The source conditions for modes 4 & 5 are similar to mode 1 & 2. Mode-6 is similar like mode-3 but both powers are available, then battery gets charging from both the sources. The modes 4, 5 & 6 battery state of charge is in between than 40-80 %, battery gets charging from solar or wind or solar

& wind power by enabling control breaker 1 & 3 from main controller and DC load getting supply from available sources. If load position is '1' load getting power from these sources, otherwise these excess energies is export to grid, and the system operating in grid connected mode otherwise its continuing with standalone mode load gets supply from the system until the above conditions gets false. Control functions are based on algorithms which are programmed from MATLAB Simulink real time kernel. Control function are similar to c programming, according to the algorithm control function was developed and block also build in MATLAB itself and the same file is transfer to speed goat real time target machine by USB. After completion of kernel process, the application is starting automatically. The complete dumping process of program from MATLAB to Real time target machine is as shown in the figure 3(b). This complete process of control will operate Where, Q_e is input charge in Ampere-seconds, Q_{e_init} is initial charge in Ampere-seconds and τ is integration time variable time in (s). Complete Simulink model of wind-solar electrical systems with different modes of output is carried out by MATLAB/Simulink software. The input is getting from PMSG the variable 24V AC supply is initially converted to DC by three phase uncontrolled bridge rectifier. The output of bridge rectifier is 20V DC because the rectifier efficiency is only 81.2%. The variable 20V DC voltage is converted into fixed 24V DC by using unidirectional boost converter, and the converter current is almost 2A. This 24V constant DC is directly supplied to BDC. The carrier and reference signal are compared, and PWM signal automatically controls the output. In the other side, the bidirectional converter operates in boost mode and input is a step-up up to 48 V DC from the input 24 V DC. Again, the input energy is further converted AC-DC and also step-up to the required level of Resistive load nearly 96 V. Whole electrical input power is directly applied to the load, then this mode is called the wind sourced output mode. The experimental platform of overall system consists of a boost converter and bi-directional converter with PMSG. The performance of the unidirectional boost and bi-directional converters are controlled by DSPIC30F4011 controller with PID control structure. The five modes result values verified with simulation results. Its outputs are almost equal to the simulation result. The system has a robust performance under changing of input wind.

Existing system of energy storage consists of different stages of power conversion with specific controller but converters only operating in closed loop but total system are operated by open loop configuration as described by (Bogdan *et al*., 1994). The drawbacks of this type of systems are effective less operation, harnessing level of natural like wind and solar power also not an efficient. Consumer side power generation is very much required to meet global power demand and to reduce the burden of power supplying authority. This system of approaches is to insist the importance of power to the consumer. Power generation from renewable sources may helpful to maintain clean and green environment which are very much helpful to the living things suggested by (Chen *et al*., 2007). The existing forms of power generation are not an efficient way in both the sides such as health and wealth. Power generation is also from renewable sources such as wind and solar to avoid global warming and environmental pollution as specified by (Sungwoo and Alexis, 2012; Bataineh and Taamneh, 2017). Power supplying authority cannot able to store power because of some disadvantages such as maintenance complexity and fault identification. But small scale of energy storage is possible in the consumer side as reminded by (Zhou *et al*., 2014; Mohamadhadi *et al*., 2016).

Wind and solar are the highest available non-renewable energies which are compensate the global power demand as described by (Bogdan *et al*., 1994). These energies are unstable in nature its needs to convert stable by a boost regulator, wind energy is converting into electrical by means of DFIG or PMSG with high efficiency as explained by (Liu and Chau, 2010; Shailendra *et al*., 2015). Conversion of solar energy into electrical requires PV panel with boost converter controlled by MPPT controller as described by (Hassan *et al*., 2016) Natural wind and solar is not a reliable energy but effective utilization is required in a stand-alone system as demonstrated by (Toshiro *et al*., 2012).

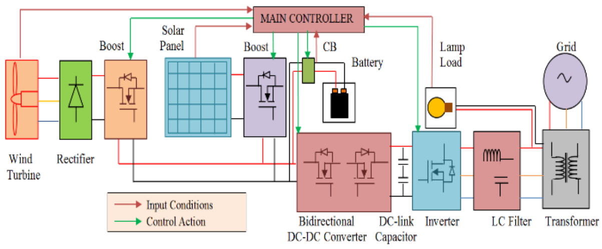

Figure 1. Block diagram of efficient electrical system

The main dis-advantage of stand-alone system is if natural energy is not available, the system meets power failure. The advantage of grid connected system is effective utilization as reminded by (Seul-Ki *et al*., 2008; Subhadarshi and Venkataramana, 2011). Grid connected system concepts is difficult with existing grid, so micro-grid concept is a modern way to integrate all the power system with an effective utilization of power as explained by (Kong and Ha, 2012; Dali *et al*., 2010). To operate system is in controlled way its need controller with good control structure which was improved by (Li *et al*., 2015). Three sources, four converters and a main control operate the system in a systematic way described by (Jing *et al*., 2016). The proposed system overcomes these draws back by means of main controller and operates the system is in closed loop. This closed loop configuration system considered the parameters such as wind speed, solar input battery state of charge and load position. Based on this consideration main control has to operate system is in closed loop by means of control breakers controlled by control algorithm. Block diagram of efficient energy storage electrical system is as shown in the figure 1.

2. Analysis of modes of operation

The complete modes of operation are explained in ten modes of operation with four input conditions such as solar irradiance (Ir), wind speed (v), Battery State of Charge (SOC) and Load position (1/0).

2.1. These conditions are inputs solar, wind and wind-solar power battery mode (1-3)

Solar power is only available source, wind power is not available because wind speed v = 0 m/s the system operates in mode-1. Solar power is not available source; wind power is only available because wind speed v > 5 m/s then the system operates in mode-2. If both powers are available, then battery gets charging from both the sources. In all the three modes battery state of charge is less than 40 %, battery gets charging from solar power by enabling control breaker 1 from main controller and DC load also getting source from the available natural sources. If AC load position is ‘1’ load getting power from grid, then the system import power from grid otherwise it continuing with standalone mode until the above conditions gets false.

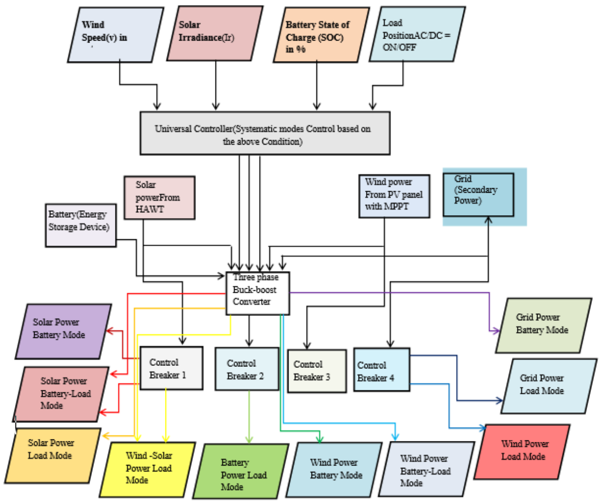

Figure 2. Modes of operation based on main controller

Electrical energy is getting from wind power is expressed in (1), rectifier output of WECS is expressed in (2)

$$P_e = \frac{1}{2} C_p(\beta, \lambda) \rho A u^3 \tag{1}$$

Wind energy conversion system (V_r) is given in (7) from PMSG output,

$$V_r = \frac{3V_m}{\pi}(1 + \cos\alpha) \tag{2}$$

The wind boost converter output (V_{bw}) is expressed in equation (3) it also output of case (i) Where V_o is open circuit voltage

$$V_{bw} = V_0 (\frac{1}{1-D}) \tag{3}$$

2.2. Solar, wind and solar- wind power battery-load modes (4-6)

The source conditions for modes 4 & 5 are similar to mode 1 & 2. Mode-6 is similar like mode-3 but both powers are available, then battery gets charging from both the sources. The modes 4, 5 & 6 battery state of charge is in between than 40-80 %, battery gets charging from solar or wind or solar & wind power by enabling control breaker 1 & 3 from main controller and DC load getting supply from available sources. If load position is '1' load getting power from these sources, otherwise these excess energies is export to grid, and the system operating in grid connected mode otherwise its continuing with standalone mode load gets supply from the system until the above conditions gets false.

Output current of photovoltaic (I_o) is given in (4),

$$I_0 = I_L - (I_d - I_{sh}) \tag{4}$$

$$I_d = I_o(\exp[\frac{qV_o + R_{se}I_o}{KT_k}] - 1) \tag{5}$$

$$I_{sh} = \frac{(V_o + R_{se}I_o)}{R_{sh}} \tag{6}$$

2.3. Solar, wind and solar- wind power load modes (7-8)

The source conditions for modes 7 & 8 are similar to mode 1, 4 & 2, 5. The modes 7 & 8 happening when battery state of charge is greater than 80 % control breaker 3 gets enabled from main controller supplying power to output from natural sources. If AC load position is '1' load getting power from these sources, otherwise these excess energies is export to grid, and the system operating in grid connected mode otherwise its continuing with standalone mode loads gets supply from the system until the above conditions gets false. The efficient or effective electrical system is in closed loop configuration.

The solar boost converter output (V_{bs}) is expressed in equation (7) it also output of case (ii)

$$V_{bs} = V_r(\frac{1}{1-D}) \tag{7}$$

The input charge of battery is expressed in the (8)

$$Q_e = Q_{e\_init} + \int -I_m(\tau)dt \tag{8}$$

2.4. Battery power load mode (9)

The source conditions for mode 9 are battery state of charge greater than 40 % wind speed v < 5 m/s and load position is '1'. Then the control breakers 2 & 3 get enabled from main controller and supplying battery power to AC load as well as DC load. If AC load position is '1' load getting power from battery, otherwise its continuing with standalone OFF mode until the above conditions gets false. The average current can be estimated by using in (9). Where I_{avg} is mean discharge current in Ampere, I_m = main branch current in Ampere and τ_1 = main branch time constant in seconds.

$$I_{avg} = \frac{I_m}{(\tau_1 s + 1)} \tag{9}$$

2.5. Grid power Battery-load mode (10)

The source conditions for mode 10 are battery state of charge less than 40 % wind speed v < 5 m/s and load position is '1'. Then the control breakers 1 & 4 get enabled from main controller and supplying grid power to AC load as well as DC load and battery. If AC load position is '1' load getting powers from grid, otherwise its continuing with battery charging mode until the above conditions gets false. The bidirectional converter output equation (10) during boost mode is derived from unidirectional boost converter. In the line-to-output transfer-function the open loop changes in the output voltage due to a variation in the input voltage during boost mode of BDC (Toshiro and Hirofumi, 2012).

$$\frac{\hat{v}_{batt}(s)}{\hat{v}_s(s)} = A_{gvf} \frac{1 + \dfrac{s}{\omega_s}}{1 + \dfrac{s}{\omega_L / C_1} + \dfrac{s^2}{\omega_L \omega_c / C_1}} \tag{10}$$

These three modes are based on the wind energy electrical system modes of operation. Stand-alone inverter mode is represented by (11)

$$G_{id} = \frac{i_L}{d_{ab}} = V_{dc} \frac{1 + sZ_{ac}C_{ac}}{Z_{ac} + s^2 L_{ac} Z_{ac} C_{ac}} \tag{11}$$

Grid supplies the power to load and also charge the battery. During this mode the power should be import from the grid (Hussein et al., 2016).

$$G_{id} = \frac{i_L}{d_{ab}} = V_{dc} \frac{2 + sZ_{dc}C_{dc}}{d_{ab}^2 Z_{ac} + sL + s^2 L_{ac} Z_{dc} C_{dc}} \tag{12}$$

In the line-to-output transfer function the open loop changes in the output voltage due to a variation in the input voltage is given by the expression (13) during buck mode of BDC (Toshiro and Hirofumi, 2012).

$$\frac{\hat{v}_s(s)}{\hat{v}_{batt}(s)} = A_{gcf} \frac{1 + \dfrac{s}{\omega_{c1}}}{1 + \dfrac{s}{\omega_{L_{cf}} / C_b} + \dfrac{s^2}{\omega_{Lcf}\,\omega_{ccf} / C_b}} \tag{13}$$

3. Control algorithm for modes of operation

Control functions are based on algorithms which are programmed from MATLAB Simulink real time kernel. Control function are similar to c programming, according to the algorithm control function was developed and block also build in MATLAB itself and the same file is transfer to speed goat real time target machine by USB. After completion of kernel process, the application is starting automatically. This process is fully depending on flowchart which is as shown in the figure 3(b). The complete dumping process of program from MATLAB to Real time target machine is as shown in the figure 3(b). This complete process of control will operate Where, Q_e is input charge in Ampere-seconds, Q_{e_init} is initial charge in Ampere-seconds and τ is integration time variable time in (s).

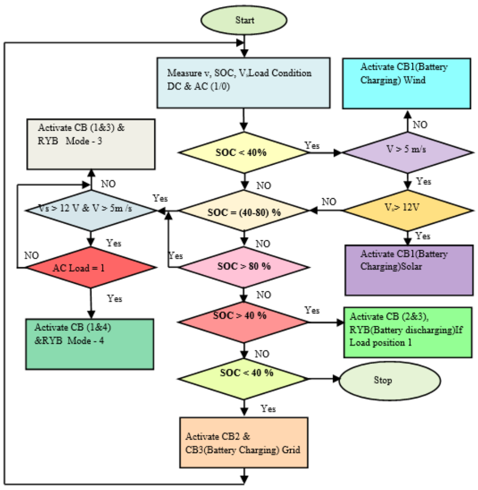

Figure 3. Modes control flow and transferring process

4. Simulation results

Complete Simulink model of wind-solar electrical systems with different modes of output is carried out by MATLAB/Simulink software which is as shown in the Figure 4. Output waveforms of the mode wind-solar electrical system are as shown in the Figure 5.

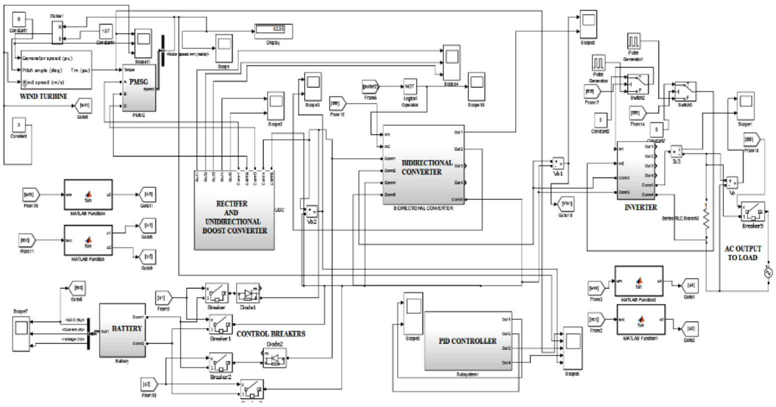

Figure 4. Simulation model

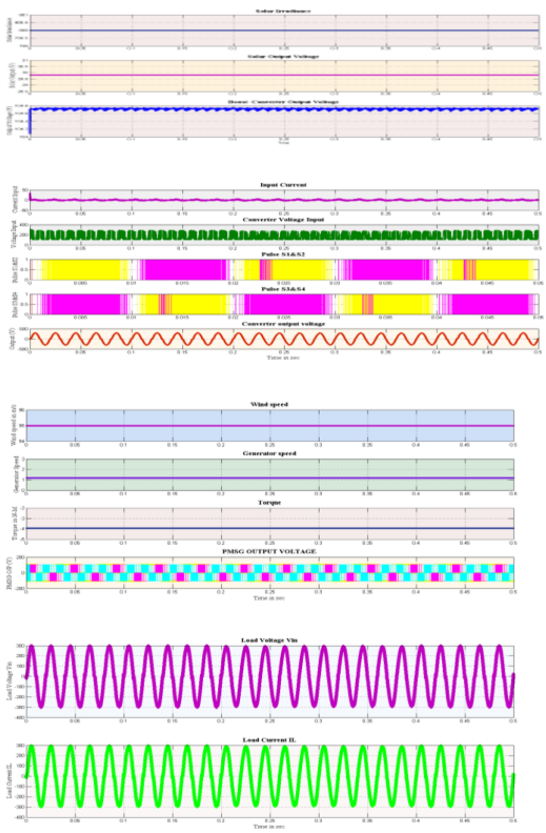

Figure 5. Simulation result

The input is getting from PMSG the variable 24V AC supply is initially converted to DC by three phase uncontrolled bridge rectifier. The output of bridge rectifier is 20V DC because the rectifier efficiency is only 81.2%. The variable 20V DC voltage is converted into fixed 24V DC by using unidirectional boost converter, and the converter current is almost 2A. This 24V constant DC is directly supplied to BDC. The carrier and reference signal are compared, and PWM signal automatically controls the output. In the other side, the bidirectional converter operates in boost mode and input is a step-up up to 48 V DC from the input 24 V DC. Again, the input energy is further converted AC-DC and also step-up to the required level of Resistive load nearly 96 V. Whole electrical input power is directly applied to the load, then this mode is called the wind sourced output mode.

5. Hardware implementation

The proposed system is implemented in hardware and the results are obtained in software level by using MATLAB Simulink software and same system is designed in hardware and the results are compared and also verified with simulation results. Hardware implementation of electrical is as shown in the Figure 6.

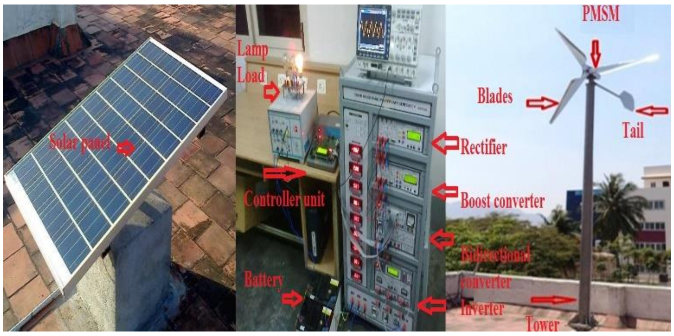

Figure 6. Hardware implementation of proposed electrical system

The wind speed at less than 5 meters per second is to reduce the wind profile parameters such as rotor speed and rotor torque. The PMSG is getting mechanical input from the wind turbine. When the wind speed is 3 meters per second the output rotor torque is 0.7 N-m and rotor speed is 37.7 radians per second.

The PMSG output is 8.3V. The wind profile consists of wind speed, rotor speed, and rotor torque has been analyzed. The PMSG model is getting input from the turbine design. When the wind speed is 5 meters per second, the outputs rotor torque is -0.4 n-m and rotor speed is 76.7 radians per second. The PMSG output is 13.6V. Hardware implementation is shown in figure7 and its result is shown in figure 8, which is compared with simulation results. The experimental platform of overall system consists of a boost converter and bi-directional converter with PMSG. The performance of the unidirectional boost and bi-directional converters are controlled by DSPIC30F4011 controller with PID control structure. The five modes result values verified with simulation results. Its outputs are almost equal to the simulation result. The system has a robust performance under changing of input wind. The results performances are verified with the simulation experimental response of the system. The experimental platform of overall system results is presented in the table 1. All the five modes result were obtained from different input wind speeds. The real time output results are almost approximately equal to the simulation results.

Table 1. hardware output results

Wind- solar energy conversion		Electrical system integrated with grid									
Modes Of Operation	Solar PV Output (V)	Wind speed (m/s)	PMSG Output (V)	Rectifier Output (V)	UDC Output (V)	Battery Output (V)	Battery SOC (%)	BDC Output (V)	Inverter Output (V)	Load Position (s)	Inverter/ Rectifier Mode
Mode	8.1	6.5	15.2	13.8	23.9	24.0	35	0	0	OFF	Stan
Mode	13.2	5.6	13.2	12.1	23.7	23.9	36	0	0	ON	Grid-
Mode	14.0	6.3	15.1	13.8	23.7	23.8	38	0	0	OFF	Stan
Mode	9.0	5.8	13.0	12.0	23.6	23.9	65	47.6	96.7	ON	Grid-
Mode	14.2	6.2	14.9	13.8	23.9	23.6	71	47.7	96.0	ON	Grid-
Mode	13.8	5.9	15.0	13.7	23.8	23.8	75	47.9	96.0	OFF	Stan
Mode	13.3	5.5	13.6	12	24.0	24.0	82	47.9	95.5	OFF	Stan
Mode	13.2	6.7	15.2	13.7	23.8	24.0	81	47.8	95.9	ON	Grid-
Mode	6.7	3.8	8.1	7.1	23.9	23.9	77	47.9	95.8	ON	Stan
Mode	5.9	3.3	8.0	7.1	24.0	23.9	39	23.9	47.6	ON	Grid-

6. Conclusion

This paper mainly focused ten modes of operation in the wind-solar electrical system for effective systematic operation. System circuits & components were designed by mathematical modelling which are represented in the form of equations. Based on the modelling system was designed in MATLAB/Simulink software and controllers were provided for all the converter circuits. Four parameter and conditions were defined, based on these parameters & conditions its operating in closed loop by means of main controller. In all the modes of operation, the system performance is verified in hardware with simulation results. The novelty of this proposed system is main controller. This controller operating the whole system in closed loop for effective utilization of available energies.

Reference

Al-Masri H. M., Ehsani M. (2016). Feasibility investigation of a hybrid on-grid wind photovoltaic retrofitting system. *IEEE Transactions on Industrial Applications*, Vol. 62, No. 11, pp. 1979-1989. https://doi.org/10.1109/TIE.2015.2438052

Bataineh K., Taamneh Y. (2017). Performance analysis of stand-alone solar dish Stirling system for electricity generation. *International Journal of Heat and Technology*, Vol. 35, No. 1, pp. 498-508. https://doi.org/10.18280/ijht.350306

Borowy B. S., Salameh Z. M. (1994). Optimum photovoltaic array for a hybrid wind PV system. *IEEE Transactions on Energy Conversion*, Vol. 9, No. 3, pp. 482-489. https://doi.org/10.1109/60.326466

Chen Y. M., Liu Y. C., Hung S. C., Cheng C. S. (2007). Multi-input inverter for grid- connected hybrid PV/wind power system. *IEEE transactions on power electronics*, Vol. 22, No. 3, pp. 1070-1077. https://doi.org/10.1109/TPEL.2007.897117

Dali M., Belhadj J., Roboam X. (2010). Hybrid solar-wind system with battery storage operating in grid–connected and standalone mode: Control and energy management-experimental investigation. *Energy*, Vol. 35, No. 6, pp. 2587-2595. https://doi.org/10.1016/j.energy.2010.03.005

Hassan F. (2016). Novel high-efficient unified maximum power point tracking controller for hybrid fuel cell/wind systems. *Applied Energy*, Vol. 183, pp. 1498-1510. https://doi.org/10.1016/j.apenergy.2016.09.114

Jing W. L., Lai C. H., Wong S. H. W., Wong M. L. D. (2016). Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: A review. *IET Renewable Power Generation*, Vol. 11, No. 4, pp. 461-469. https://doi.org/10.1049/iet-rpg.2016.0500

Kim S. K., Jeon J. H., Cho C. H., Ahn J. B., Kwon S. H. (2008). Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer. *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 4, pp. 1677-1689. https://doi.org/10.1109/TIE.2007.907662

Kong N., Ha D. S. (2012). Low-power design of a self-powered piezoelectric energy harvesting system with maximum power point tracking. *IEEE Transactions on Power Electronics*, Vol. 27, No. 5, pp. 2298-2308. https://doi.org/10.1109/MCAS.2017.2757081

Li P., Dargaville R., Liu F., Xia J., Song Y. D. (2015). Data-based statistical property analyzing and storage sizing for hybrid renewable energy systems. *IEEE Transactions on Industrial Electronics*, Vol. 62, No. 11, pp. 6996-7008. https://doi.org/10.1109/TIE.2015.2438052

Liu C. H., Chau K. T. (2010). An efficient wind–photovoltaic hybrid generation system using doubly excited permanent-magnet brushless machine. *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 3, pp. 831-839. https://doi.org/10.1109/TIE.2009.2022511

Subhadarshi S., Venkataramana A. (2011). MW resource assessment model for a hybrid energy conversion system with wind and solar resources. *IEEE Transactions on Sustainable Energy*, Vol. 2, No. 4, pp. 383-392. https://doi.org/10.1109/TSTE.2011.2148182

Sungwoo B., Alexis K. (2012). Dynamic modeling and operation strategy for a microgrid with wind and photovoltaic resources. *IEEE Transactions on Smart Grid*, Vol. 3, No. 4, pp. 1867-1877. https://doi.org/10.1109/TSG.2012.2198498

Tiwari S. K., Singh B., Goel P. K. (2015). Design and control of autonomous wind–solar system with DFIG feeding 3-phase 4-wire loads. *Proceedings of the Annual IEEE India Conference (INDICON), New Delhi, India*. https://doi.org/10.1109/INDICON.2015.7443822

Toshiro H., Hirofumi M. (2012). Standalone hybrid wind-solar power generation system applying dump power control without dump load. *IEEE transactions on Power electronics*, Vol. 50, No. 2, pp. 988-998. https://doi.org/10.1109/TIE.2011.2159692

Zhou T. P., Sun W. (2014). Optimization of battery super capacitor hybrid energy storage station in wind/solar generation system. *IEEE Transactions on Sustainable Energy*, Vol. 5, No. 2, pp. 408-416. https://doi.org/10.1109/TSTE.2013.2288804