Modeling and Simulation of Grid Synchronized DC Microgrid with Wind and Solar Resources

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Abstract- The increased usage of fossil fuels has caused a concern for the depletion of such fuels, and has a detrimental impact on the environment by producing greenhouse gases. These major concerns have turned worldwide focus towards performing innovative research in renewable energy resources so that these could readily replace the depleting fossil fuels. Recently, the research and the resulting developments in the field of power electronics has allowed the use of integrating multiple renewable resources, such as wind and solar, for efficient distributed generation. Commercially sold systems have separate inverters for each renewable resource, thus increasing the system complexity, cost and power losses. Replacing these separate inverters with one inverter will reduce the system complexity, cost and power losses. Therefore, this paper studies the modeling and simulation of grid connected DC microgrid with wind and solar resources. The study analyses the modeling of each module: permanent magnet synchronous generator (PMSG) wind energy systems with diode rectifier; PV panels; DC-DC boost converters; voltage source inverter (VSI). The entire system is simulated with Powersys library of Simulink-MATLAB.

Keywords- **:** DC Microgrid, Wind Power, Solar Power, Boost Converter, Voltage Source Inverter.

I. INTRODUCTION

Rising demand for energy coupled with depleting fossil fuels and increased awareness for preserving the environment, has increased the need for research and advancement in sustainable, cleaner, pollution free, renewable resources. Government incentives and the research and the resulting developments in the field of power electronics has allowed wind and solar energy to become the most widely researched and deployed technologies [1]. The natural changes in wind and solar makes any such energy systems complementary sources rather than base sources. Therefore, integrating these two resources increases the reliability and allows for better unremitting supply of power to the connected loads. However, even connecting these two resources is not enough for an uninterruptable power supply to the load, and a battery bank or connection with the grid is required. The grid synchronization for distributed generation can essentially act as a virtually connected battery and also allows for selling the excess energy generated by the renewable resources back to the grid and thus reducing the overall cost of the system or even be profitable in the future [2].

The goal of this paper is to present a typical grid-tied DC microgrid by considering an example problem which is both financially (as storage source is not employed) and technically feasible for solving our domestic energy crises.

It takes into account a power generation, consumption and even dispatch to AC grid on a typical day. This research work studies the modeling and simulation of grid connected DC microgrid with wind and solar resources. The study analyses the modeling of each module: permanent magnet synchronous generator (PMSG) wind energy systems with diode rectifier; PV panels; DC-DC boost converters; voltage source inverter (VSI). The Section II presents the literature review with an insight into the relevant state of the art. The architecture of the proposed DC microgrid and the mathematical modeling of wind and solar energy system are presented in Section III. Section IV presents the control design and maximum power point tracking (MPPT) techniques for wind and solar resources. The entire system is simulated with Powersys library of Simulink-MATLAB in Section V. Finally, this paper is concluded with Section VI.

II. LITERATURE REVIEW

Microgrids with distributed generation has the additional advantage of generating clean and sustainable energy close to the load where it is consumed which reduces technical losses of electrical transmission [3]. Furthermore, renewable energy systems can be installed on residential premises such as rooftops thus saving the cost of acquiring and operating large space for centralized energy generation [4].

Until recently, alternating current (AC) power has ruled the world for its ability to be transformed easily to higher voltage levels and thus transmitted from large central generating stations to consumers located faraway [5]. However, the majority of the consumer equipment today works on DC and the renewable generation is also providing DC power. Therefore, to provide power to DC operated consumer equipment from DC power generating renewable resources for the current AC model, requires power conversion first from DC-AC from renewable resources and then from AC-DC for powering DC equipment [6]. This power conversion results in substantial power losses which can be eliminated by a DC microgrid [7]. Additionally, this DC microgrid can be connected to the AC grid by using a single high-efficiency voltage source inverter to allow for better reliability and selling excess energy to the grid for better economic feasibility [8,9]. An energy management strategy which is based on PV/fuel cell and energy storage DC microgrid but lacks synchronization mechanism with AC grid [10]. Different economic load dispatch strategies for a DC microgrid (grid tied) can be employed for optimization. [11] presents analysis of a charge storage source with a grid-connected DC Microgrid with tariff reduction and enhancing battery life. However, there is no sufficient details of a VSI unit that provides grid synchronization. [12] presents a similar AC microgrid with integrated distributed VSIs with a centralized management system control strategy for maintaining power quality and tariff variation on a typical day. It tends to differs from the proposed model as it uses a distributed/ separate control strategy for PV and Wind units. [13] presents a similar study on a scaled down DC microgrid on power management and control strategies. [14] simulates an AC/DC microgrid model which can be used a base case for analyzing parameters such as power flow analyses, power quality, load dispatch strategies, etc. but it does not offer any resource model analysis.

III. MODELING THE GRID SYNCHRONIZED DC MICROGRID

This section describes the architecture of the proposed DC microgrid and the mathematical modeling of the wind and solar renewable resources.

A. Architecture of the Proposed DC Microgrid

The architecture of the proposed DC microgrid is displayed in Fig. 1. Permanent magnet synchronous generator (PMSG) wind turbine is connected to the DC microgrid with the use of a diode rectifier and a DC-DC boost converter whereas the PV panels are connected with just a DC-DC boost converter [9].

B. PV Unit Model

The PV unit is formed by connecting in parallel and series many PV cells. Each individual PV cell is essentially similar to a PN junction diode which generates electric current when light is shined on it [15]. The PV cell is modeled by an equivalent circuit as depicted in Fig. 2.

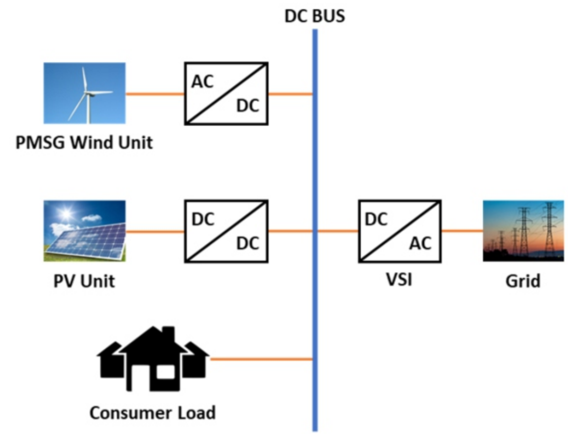

Fig. 1. Architecture of the proposed DC microgrid

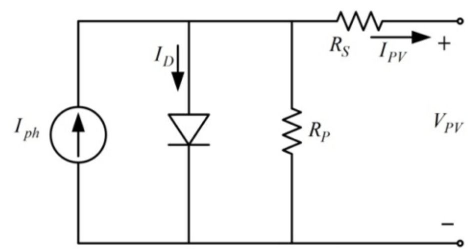

Fig. 2. Equivalent circuit schematic for a PV cell

From the above figure the following equation is deduced:

$$I_D = I_0\{-1 + exp\ exp\ [(R_S I_{PV} + V_{PV})A_{PV}]\} \quad (1)$$

The above equation is formed on the suppositions that the temperature is considered to be 300°K and the parallel resistant R_p is too high which means I_{sh} can be neglected.
Therefore:

$$I_{R_p} = \frac{R_S I_{PV} + V_{PV}}{R_P} \quad (2)$$

$$I_{PV} = I_{ph} - I_{R_P} - I_D (3)$$

Various parameters of the PV unit are given as:

$I_0 = 2.35e - 8\ A$

$A_g = 0.87\ V^{-1}$ (300°K)

$I_{ph} = 4.682\ A$ (Insolation = 100 %)

$R_S = 0.4114\ \Omega$

The output voltage equation for the PV unit can be written as:

$$V_{PV} = -I_{PV}R_S + \frac{1}{Ag} ln \left(\frac{I_{ph}-I_{PV}}{I_0} + 1\right) \quad (4)$$

The P-V and I-V characteristics of the PV system displayed in Fig. 3 show that the system is non-linear and depends on insolation percentage.

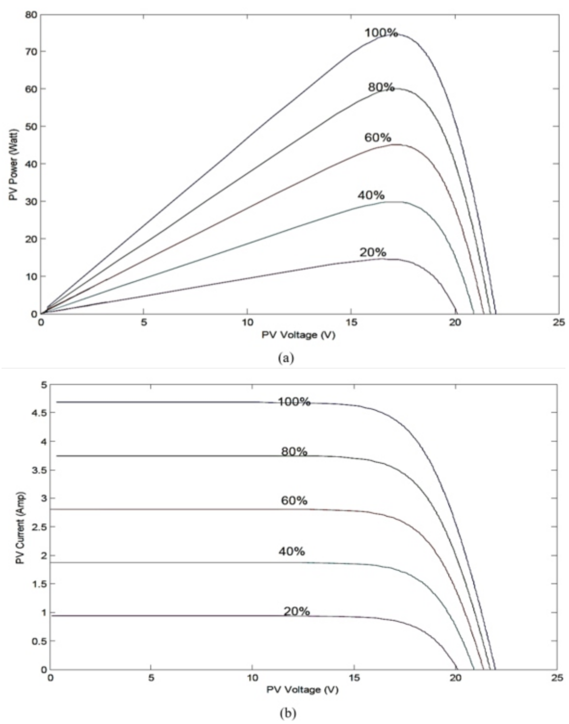

Fig. 3. Characteristics of PV for different insolation (a) P-V (b) I-V

C. Wind Unit Model

The mechanical power converted from wind power by a wind turbine is expressed as [16]:

$$P_m = 0.5\pi\rho L^2 V_w^3 C_p(\beta, \lambda) \quad (5)$$

$$\lambda = \frac{L \cdot \omega_{mec}}{V_w} \quad (6)$$

$$\lambda_i^{-1} = -\frac{0.035}{1+\beta^3} + (\lambda + 0.05\beta)^{-1} \quad (7)$$

$$C_p = 0.517 \, exp \, exp \, (-21\lambda_i^{-1}) \left(116\lambda_i^{-1} - 0.4\beta^{-5}\right) + 0.007\lambda \quad (8)$$

In the above equations: L is the turbine's radius, ρ denotes air density, V_w denotes speed with which the wind is blowing. The coefficient C_p essentially denotes the efficiency of power extraction for the wind turbine. This coefficient theoretically has a value of 0.59 but in practical scenarios it is 0.4-0.45 [17]. From the above equations, it is evident that the value of C_p or ouput power of the wind turbine is dependent on pitch angle β, tip-speed ratio λ and rotational speed of the turbine ω_{mec}. Therefore, for different wind speeds the value of the optimum mechanical rotational speed changes, this is depicted in Fig. 4.

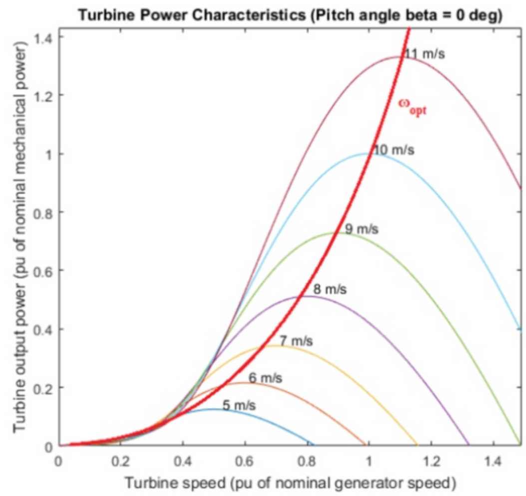

Fig. 4. Wind turbine rotational speed vs power

IV. Control Algorithms of Units

This section explains the various control techniques used for different units of the DC microgrid.

D. PV Unit Control

This paper implements the Perturb and observe (P&O) method of maximum power point tracking (MPPT). This is the most utilized method and selected for its effectiveness, simplicity and the ease with which it can be implemented [18].

In this method, the values of current and voltage are measured initially and a mean algorithm is used which smoothen the signal and increases the stability. These values are then used to calculate the mean power value. The value of the mean power is compared with the previous value. After this comparison the voltage value is compared with the previous voltage value. The duty cycle for the DC-DC boost converter connected with the PV array is then increased or decreased based on these two comparisons. The duty cycle is increased or decreased with a fixed value represented by ΔD. This value is selected on the basis of the speed and accuracy of the algorithm. Smaller values of ΔD will better approximate the maximum power point but it will also take longer to reach the maximum point. On the contrary a large value will reach the maximum power point more quickly but it will fluctuate around the maximum power point in greater steps and thus can lead to system instability [19]. The flowchart for this MPPT technique is depicted in Fig. 5.

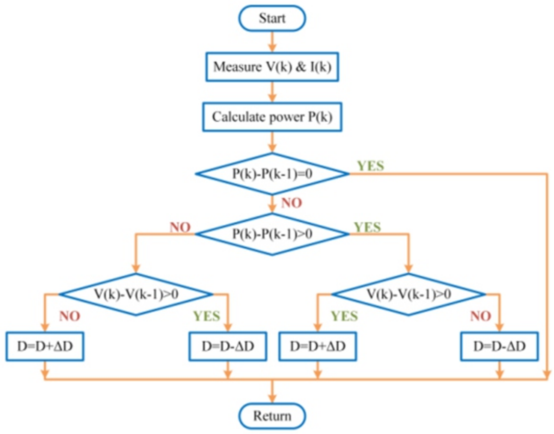

Fig. 5. MPPT flowchart for PV unit

E. Wind Unit Control

Analyzing the graphs of turbine speed and output mechanical power of the turbine, depicted in Fig. 6; it can be deduced that for different wind speeds there is a particular optimum mechanical rotational speed ω_{opt}. Operating the wind turbine at that rotational speed will extract the maximum power that the turbine can produce for that particular wind speed [20]. This ω_{opt} is dependent on a constant denoted by K_{opt}. The value of this K_{opt} is dependent upon the λ_{opt} and $C_{p_{max}}$. Substituting these values into (5), the equation for the output power can be written in terms of K_{opt} and ω_{opt} as:

$$P_{m_{opt}} = \frac{0.5\pi\rho L^5 \omega_{opt}^3 C_{p_{max}}}{\lambda_{opt}^3} = \omega_{opt}^3 \cdot K_{opt} \qquad (9)$$

The relation between optimum torque and optimum power output is given as:

$$P_{m_{opt}} = \tau_m \cdot \omega_m \qquad (10)$$

$$\tau_{m_{opt}} = \frac{0.5\pi\rho L^5 \omega_{opt}^2 C_{p_{max}}}{\lambda_{opt}^3} = \omega_{opt}^2 \cdot K_{opt} \qquad (11)$$

Considering a single mass model of the drive train, which is sufficient for focusing on the electrical power generation dynamics of the wind turbine, the dynamic equation for the torque transmission is given as:

$$\frac{d}{dt}\omega_m = \frac{\tau_e - B\omega_m - \tau_g}{J_{eq}} \qquad (12)$$

Where B, τ_e and J_{eq} are the damping coefficient, electromagnetic torque generated by the PMSG and equivalent rotational inertia respectively. From the above equation it is clear that controlling the electromagnetic torque of the PMSG controls the rotational speed of the wind turbine and in turn can be used to take the power generated by the wind turbine to its maximum power point. The equation describing the electromagnetic torque of the PMSG is described as:

$$\tau_e = 1.5N_p\left(i_q\phi_{PM} + (L_d - L_q)i_q i_d\right) \qquad (13)$$

Where ϕ_{PM} and N_p are the permanent magnet flux and number of poles respectively. The current I and inducatance L are split into their respective dq-axis components. Therefore, controlling the current of the PMSG by varying the duty cycle of the connected DC-DC boost converter changes the electromagnetic torque and can be used to implement the optimum torque MPPT technique [20].

V. SIMULATION

The DC microgrid with each of its renewable units modeled above is simulated using Powersys library of Simulink-MATLAB.

F. PV Unit

The specification for the PV unit used in this study is described in the table given below:

Table I. PV Unit Specifications

Description	Symbol	Value
V_{PV}	PV unit voltage	274.5V
P_{PV}	PV unit power	100KW
n_p	Parallel panels in the PV unit	5
n_s	Series panels in the PV unit	64
C_{B-PV}	Boost-converter capacitance	1000μF
L_{B-PV}	Boost-converter inductance	5mH
f_B	Frequency of the boost-converter	5KHz

The structure of the PV unit in Simulink-MATLAB is given in Fig. 6.

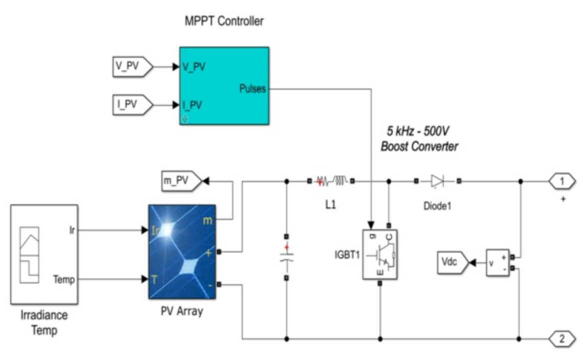

Fig. 6. Structure of the PV unit

G. Wind unit

The specifications for the wind unit used are described in the table given below:

Table II. Wind Unit Specifications

Description	Symbol	Value
V_w	Rated operational wind speed	13m/s
P_w	Rated output power of the wind unit	100KW
L	Length of the wind turbine blade	13m

N_p	Poles pairs of the PMSG	24
C_{B-w}	Boost-converter capacitance	1000μF
L_{B-w}	Boost-converter inductance	0.1mH

The structure of the wind unit in Simulink-MATLAB is given in Fig. 7.

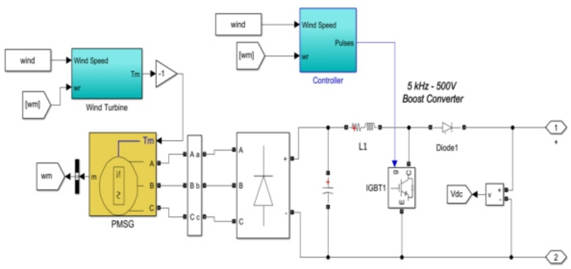

Fig. 7 Structure of the wind unit

satisfactory operation of the PV unit and its associated DC-DC boost converter as well as the P&O MPPT technique used in the unit, the changing irradiance level of a typical day was applied to the unit. The irradiation for a typical day starts increasing slowly with sun rise and reached a peak value at noon, after which the irradiance starts to decrease and reaches zero at sunset. The output of the PV unit with this changing irradiance is depicted in Fig. 9. It can be seen that the output power changes with the irradiance. The Irradiance experiences a cyclic change over it span (the curve contracts or expands) in different seasons. It also depends on the location and related geographical coordinates. It is however important to mention here that the performance of the PV unit seems to correlate with irradiance. It can be seen from Fig. 9 that PV unit

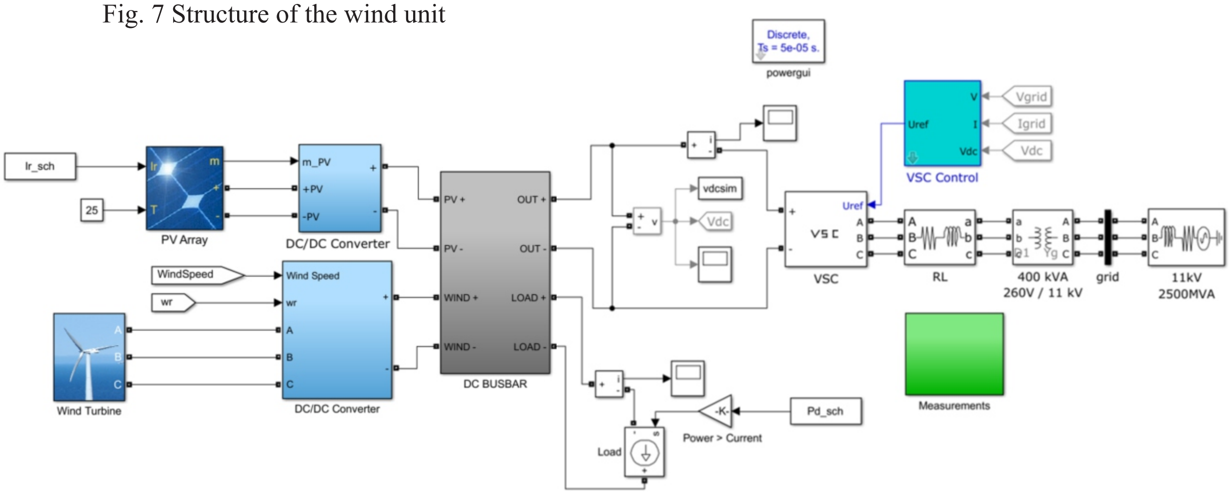

Fig. 8 Architecture of the entire DC microgrid

H. DC Microgrid

The specifications for the entire DC microgrid used in this study are described in the table given below:

TABLE III. DC Microgrid Specifications

Description	Symbol	Value
E	Voltage of the utility grid	11KV
V_{dc}	Voltage at the DC bus	500V
VA_{TF}	Power rating of the line transformer	300 KVA
V_{1-2}	Voltage ratio of the line transformer	260V/11K V
R	Resistance of the line filter	1mΩ
L	Inductance of the line filter	45μH

The structure of the entire DC microgrid in Simulink-MATLAB is given in Fig. 8. The system was simulated with a time sample of 5e-05sec which resulted in a quick and accurate simulation of the entire DC microgrid system performance. To verify the voltage increases as the duty cycle for the boost converter is decreased. This phenomenon indicates that P&O-MPPT algorithm for PV unit is performing effectively.

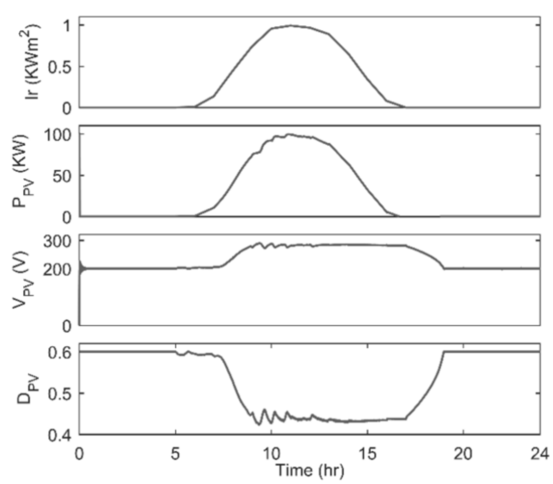

Fig. 9 PV unit simulation performance results

The operation of the DC-DC boost converter and that of the MPPT for the wind unit is verified by changing the wind speed. The operation of the pitch control is also verified when the wind speed exceeds 13m/s and the power is kept at the rated 100KW as seen in the Fig. 10. This helps to demonstrate efficient pitch controller performance that is evident from the constant power output when wind power increases beyond 13m/s.

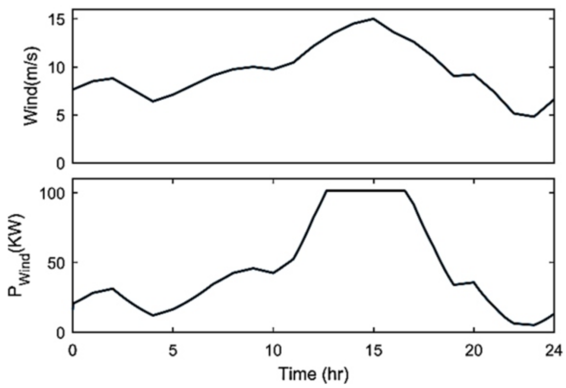

Fig. 10. Wind unit simulation results

The operation of the DC voltage control of the VSI is shown in Fig. 11. It can be seen that the voltage is held regulated at 500V. This demonstrates that the P&O provides a fairly synchronized with very few spikes and low switching and harmonic components.

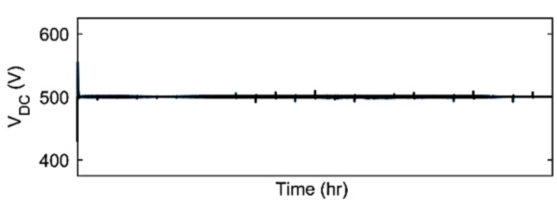

Fig. 11. VSI simulation result

VI. Conclusion

This study presents modeling and simulation of grid synchronized DC microgrid with wind and solar renewable resources. This paper analyses the modeling of each unit: permanent magnet synchronous generator (PMSG) wind energy unit with diode rectifier; PV panels; DC-DC boost converters; VSI. The entire system is simulated with Powersys library of Simulink-MATLAB. The system is simulated with different wind speeds and insolation levels and performed effectively. The DC bus voltage of the entire microgrid is maintained constant at 500V with different operating conditions. The future work includes load forecasting and simulating different scenarios with more than multiple Wind and PV units and including hybrid (AC/DC) microgrid bus bar systems.

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