Assessment of Resiliency by incorporating DGs in Power Network using Graph Theoretic Approach

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***Abstract*— As the Power System Network/Infrastructure is continuously growing, so does its complexity. As a result, it is more prone to various adverse events which leads to disruption of power flow or continuity. In this paper an approach towards the power system resiliency has been tried with the help of betweenness centrality and minimum spanning tree concept of graph theory. Betweenness centrality of a power system network have been considered here to analyze resiliency of the system in order to find the most critical bus(es) or node(s) and along with that minimum spanning tree based on active power flow has been taken to find out the critical lines, so that what are the effects towards its associated transmission line(s) can be observed precisely. Also, the critical transmission lines based on Minimum Spanning Tree have been taken into consideration in order to harden them. In order to implement these simulations have been carried out on IEEE 57 Bus System.**

Keywords— Resiliency, distributed generation, betweennesss centrality, minimum spanning tree, power flow.

I. Introduction

Electricity has become one of the basic necessities of our daily life, our social life as well as our economic life. So, any disruption to electricity can affect our life. Any adverse events in power system cannot be prevented beforehand, but what can be done is to minimize the impacts and measures can be taken to reduce the chance of repetitive occurrence of some adverse events. Also, the most important part is to bring back the system to its former normal state as soon as possible. Resiliency of power system is all about this.

These disruptions to electricity often lead to short term outages, cascading outages [1], long term outages. So, to understand the causes and effects and to take proper measures, a framework [2] is needed which can help to analyze the resiliency of the power system. For that reason, a quantitative analysis [3] has to be made where we can see how much impact can be there for certain adverse events. To do this a vulnerability analysis [4] needs to be carried out to identify the critical node(s) and line(s). After any disruptions while restoring, in view of resiliency, minimum spanning tree [5] can help to reduce the computational time. Also, we can incorporate distributed generation [6] to restore to the critical loads quickly.

In this paper the threat to the power system has been analyzed intentionally by removing the critical lines associated with highest betweenness bus from the system. The abrupt changes in the active power flow and bus voltage is observed. Finally by introducing the distributed energy resources or DGs to the system, the active power flow and bus voltage improvement has been observed. Thus for making a resilient power system distributed energy resources may be one of the best measure for power system personnel.

II. Power System Load Flow Analysis

It is an analysis on the power system to obtain the complete network solution for present scenario as well as future prediction. Through this analysis voltage profile and power angle at each bus is obtained. Also, active reactive power flows through lines are observed. This load flow analysis is based on buses which are associated with voltage, power angle, active power and reactive power. Out of these four two are specified for each bus.

- Generator Buses are those where generators are connected and where active power and voltage are defined.
- Load Buses are those where active power and reactive power are defined.
- Slack Buses are those where voltage and power angle are specified. Normally a generation bus with high value of active power is considered as slack bus.

A. Newton Raphson Method

The Newton Raphson method is one of the most useful tools which can be used to solve algebraic non-linear equations of load flow analysis. In this method, the solution(s) is (are) approached by transforming initial non-linear problem into a sequential linear one. In this method, the convergence to solution is very fast and number of iterations is also less. the accuracy of the solution reached by this method is also very good. These are the main benefits of Newton Raphson method. Initially some values are guessed then with the help of Newton Raphson method the next guess is determined and the process will go on until suitable solution(s) is(are) reached within a prescribed toleration limit.

III. Graph Theoretic Approach

Power system can be modeled as a weighted graph. Where nodes being considered as bus and edges being considered as lines. Weights can be impedances, admittances or active power or reactive power flow value through the lines. Depending on the weights shortest paths, betweenness centrality, clustering coefficients, minimum spanning trees can be obtained. This topological model helps to identify the weakest bus or line which is prone to failure with small disturbances. To strengthen the power network or to enhance the resiliency, graph theoretic approach takes a leading role in this aspect.

A. Betweenness Centrality

Betweenness Centrality of a node can be the measurement of how many times that node will appear while travelling between two other nodes based on the shortest path between them [7].

$$B_{(e)} = \sum_{x,y \neq e} \frac{N_{xy}(e)}{N_{xy}} \tag{1}$$

Where, $B_{(e)}$ is the betweenness centrality of node e, $N_{xy}(e)$ is the number of shortest paths between node x and y, passing through node e and N_{xy} is the total number of shortest paths between node x and y. This betweenness centrality feature can be set as a criterion to find critical node(s).

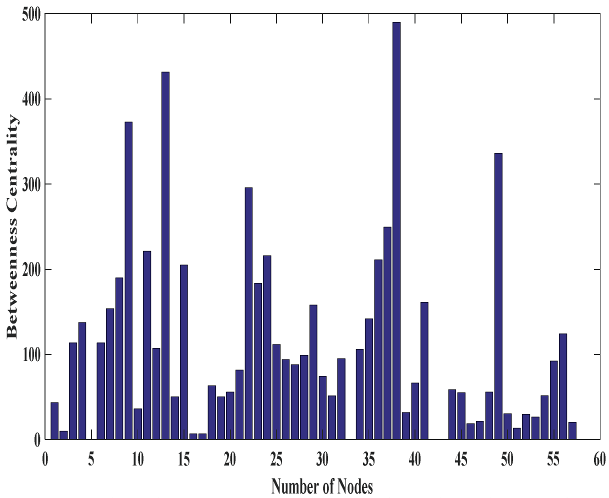

Fig. 1. Plot of betweenness centrality of nodes with number of nodes in IEEE 57 bus test system

B. Minimum Spanning Tree

Minimum Spanning Tree is a subset of a connected graph in which all the nodes or vertices are connected through minimum possible connecting lines among them or edges, so that no cycle is formed. Here in this paper Kruskal's algorithm is followed to obtain the minimum spanning tree of IEEE 57 Bus System based on active power flow (considered as weight) through lines [8].

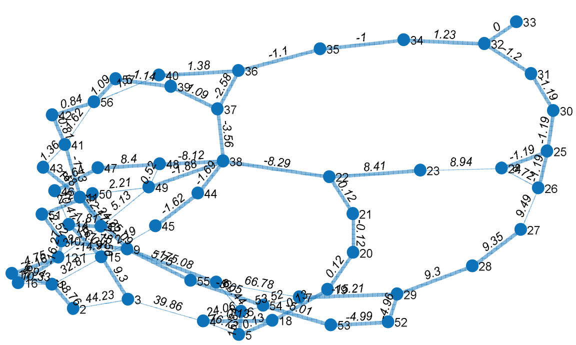

Fig. 2. Plot of minimum spanning tree based on active power flow through lines calculated with the help of Newton Raphson method in IEEE 57 bus test system

Steps for calculating Minimum Spanning Tree using Kruskal's algorithm:

- First of all loops are removed
- Then all the edges are sorted based on the weightage (active power flow value) in ascending order.
- Then the edge(s) having least weight(s) has(have) been started to connect in between their respective nodes. Also, it is kept in check that no circuit or cycle is formed. If connecting any edge will form circuit that edge need to be avoided.
- Then with the next edge with higher weightage the process of addition of edges will be preceded. Again, no circuit or cycle formation condition is checked. It is continued throughout till the minimum spanning tree is formed.

IV. Distributed Generation

Distributed generations also known as distributed energy resources, are typically stay within the distribution system as parallel electrical utility or standalone system. They are in the range of 3KW to 50MW and generally use renewable energy sources like solar, wind, biomass, geothermal etc [9]. Although all these distributed generations do not supply continuous and steady power, still they play a major role as they are eco-friendly and an important part of microgrid.

In recent times distributed generations is not considered for vulnerability assessment of a power network. But in past few years the occurrence of the high impact low frequency events are increased day by day. This undesired events causes blackout, economical and structural damages to the critical infrastructure as well as power grid. For the huge area coverage of the power network the load centers are far away from the generation part of the grid, which caused a low reliability of the far distant consumers during these high impact low frequency events. For overcoming these situations the adoption of distributed generation is a good choice for the existing power grids [10]. It can reduce the power balance in the long transmission line and make the grid more reliable. Along with this distributed generations can enhance the resiliency of the power network. Also by incorporating the distributed generations in the power network the structural and topological properties of the network also changes.

V. Resiliency Assessment

Now a day's critical infrastructure is fully dependent on the power sector. Blackout for a few hours causes a huge loss in economic as well as industrial sector. High impact low frequency events damaged the entire power network. To protect the consumers form the undesired events researcher investigates the possibility to enhance the resiliency of the power sector, which harden the grid as well as withstand the high impact of the event. By implementing distributed energy resources (DERs) to the power grid, the resiliency can be improved. At the time of undesired events the consumer will get the power from the DGs and critical infrastructure will also utilize that power. Here the concept of adding distributed generations to the critical bus to enhance the resiliency of the network is being implemented

[3]. The critical bus can be identified by the betweenness centrality of the node and at that node distributed generations can be added one by one to verify the improvement of the voltage profile. Thus the assessment of resiliency of the network is investigated [4].

VI. Simulations and Results

Here, in this paper, IEEE-57 Bus System has been taken as test system for consideration. It contains 57buses and connecting lines among those 57 buses. Out of these 57 buses generators are connected in 7 buses.

We have considered active power flow in the lines and voltage profile of buses as our base of consideration in this paper. We have taken the help of Newton Raphson method, Betweenness Centrality and Minimum Spanning Tree as the tool to analyze Resiliency in IEEE 57 Bus System.

- First, Newton Raphson has been run on IEEE 57 Bus System with standard data and the voltage in Buses and active power flow in the lines has been noted down.
- Next, the most critical node has been found out using Betweenness Centrality and has been taken as main priority consideration. Because as per the definition of betweenness centrality, the node with highest betweenness centrality has the most considerable influence in the network it lies within. Also, any disruption to that node can create max disruption within the network.
- Next, Minimum Spanning Tree has been found out using Kruskal's Algorithm.
- Now, four case studies have been carried out.
- First, one line has been removed and the changes in bus voltages and power flow in some adjacent lines have been observed. As for the reason for this consideration, it is found that due to natural disaster or man-made events or some faults transmission line gets disconnected.
- Second, three distributed energy resources or DGs of 10 MW have been added one by one to a node which has highest betweenness centrality and the changes in bus voltages and power flow in adjacent lines have been observed after each addition. The reason behind this consideration is that, sometimes to meet some excess demand or to meet the critical load distributed energy resources or DGs are incorporated to the system.
- Third, another line has been removed consecutively and the changes in bus voltages and power flow in some adjacent lines have been observed. The line removed from the third highest betweenness bus.
- Fourth, one distributed energy source or DG of 30 MW have been added to the node which has third highest betweenness centrality and the following changes has been observed. Improvement in bus voltage is observed and the enhancement of resiliency of the system is ensured.

TABLE I. Comparison of Active Power Flow at Normal State and When Line 38-22 is Removed from IEEE 57 Bus Test System

Line	*Active power flow at normal condition (MW)*	*Active power flow when line 38-22 removed*	*Difference (%)*
37-38	-3.56	-5.19	45.79
38-48	-8.12	-4.97	-38.79
38-49	-1.88	-0.37	-80.32
38-44	-1.69	0.32	-118.93
22-23	8.41	2.21	-73.72
21-22	0.12	2.22	1750
9-10	-17.75	-18.51	4.28
9-11	-24.25	-25.52	5.24
9-12	-14.91	-15.39	3.22
9-13	-22.09	-23.2	5.02
9-55	-5.75	6.3	-209.57

From the Fig. 1, it is evident that the highest betweenness bus is node 38 in the IEEE 57 bus test system. The line connected with node 38 and node 22 is deleted and the comparison in voltage profile is observed in Fig. 3. The change in active power flow is obtained in the Table. I.

In the next step the DGs are added one by one in that highest betwenness node 38 in IEEE 57 bus test system. First 10 MW DG is added to the node 38 and the comparison in power flow is shown in Table. II and the improvement in volatage profile is observed from Fig. 4.

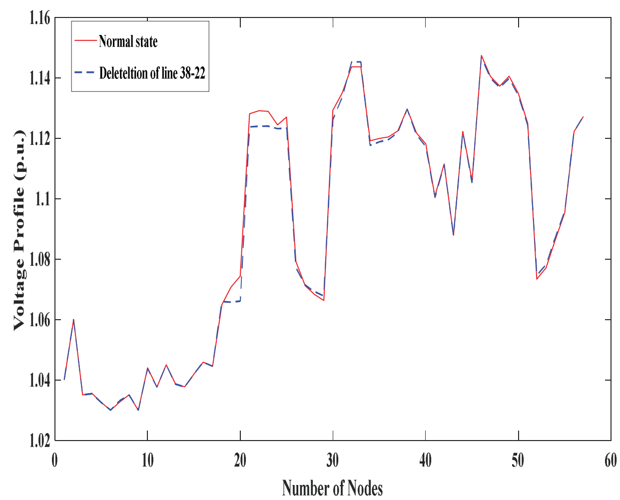

Fig. 3. Comparison of Voltage Profile before and after deletion of line 38-22 in IEEE 57 bus test system

TABLE II. Comparison of Active Power Flow at Normal State and When 10 MW DER/DG is Added to Node 38

Line	*Active power flow at normal condition (MW))*	*Active power flow when 10 MW DER/DG is added to node 38*	*Difference (%)*
37-38	-3.56	-4.09	14.89
22-38	-8.29	-9.35	12.79
38-48	-8.12	-4.23	-47.91
38-49	-1.88	-0.08	-95.74

Line	*Active power flow at normal condition (MW))*	*Active power flow when 10 MW DER/DG is added to node 38*	*Difference (%)*
38-44	-1.69	1.03	-160.95
22-23	8.41	9.14	8.68
21-22	0.12	-0.2	-266.67
8-9	-175.08	-175.19	0.06
9-10	-17.75	-17.77	0.11
9-11	-24.25	-24.54	1.20
9-12	-14.91	-14.6	-2.08
9-13	-22.09	-22.17	0.36
9-55	5.75	5.71	-0.70

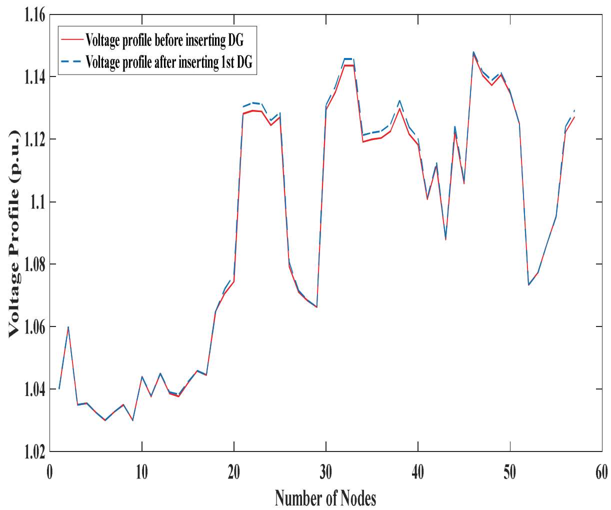

Fig. 4. Comparison of Voltage Profile before and after addition of 1st DG of 10 MW to the node 38 in IEEE 57 bus test system

Second DG of 10 MW is again added to the highest centrality bus 38 and the comparison of active power flow in some adjacent lines is presented in Table. III.

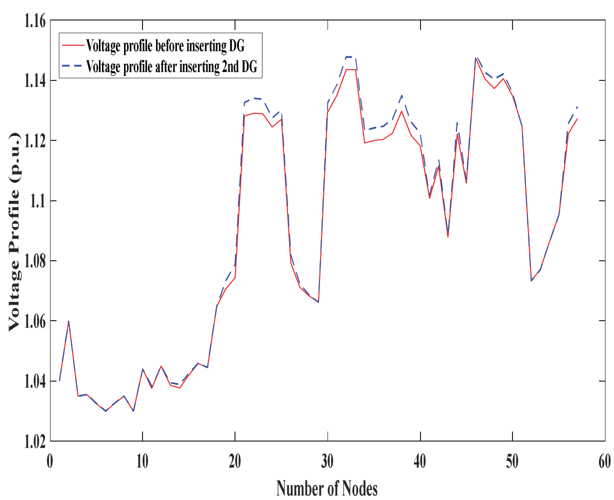

Fig. 5. Comparison of Voltage Profile before and after addition of 2nd DG of 10 MW to the node 38 in IEEE 57 bus test system

TABLE III. COMPARISON OF ACTIVE POWER FLOW AT NORMAL STATE AND WHEN TWO 10 MW DER/DG IS ADDED TO NODE 38

Line	*Active power flow at normal condition (MW))*	*Active power flow when 2*10 MW DER/DG is added to node 38*	*Difference (%)*
37-38	-3.56	-4.62	29.77
22-38	-8.29	-10.4	25.45
38-48	-8.12	-0.34	-95.81
38-49	-1.88	1.72	-191.49
38-44	-1.69	3.75	-321.89
22-23	8.41	9.87	17.36
21-22	0.12	-0.53	-541.67
8-9	-175.08	-175.29	0.12
9-10	-17.75	-17.78	0.17
9-11	-24.25	-24.83	2.39
9-12	-14.91	-14.29	-4.16
9-13	-22.09	-22.24	0.68
9-55	5.75	5.66	-1.57

Improvement of voltage profile in some adjacent lines is plotted in Fig. 5. At this point of time total 20 MW distributed generators are added to the bus 38 in IEEE 57 bus test system.

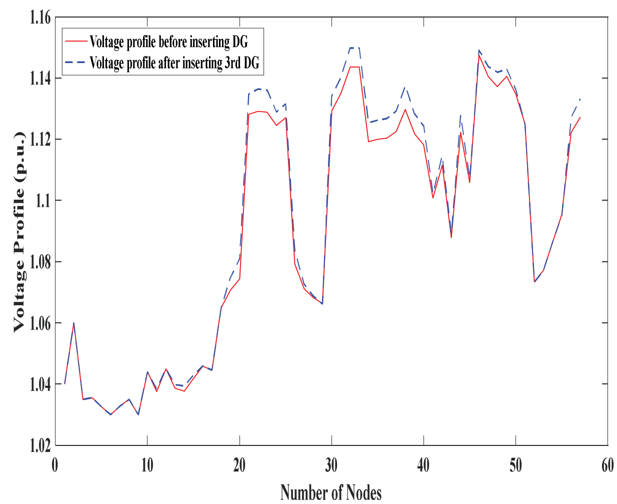

Fig. 6. Comparison of Voltage Profile before and after addition of 3rd DG of 10 MW to the node 38 in IEEE 57 bus test system

TABLE IV. COMPARISON OF ACTIVE POWER FLOW AT NORMAL STATE AND WHEN THREE 10 MW DER/DG IS ADDED TO NODE 38

Line	*Active power flow at normal condition (MW))*	*Active power flow when 3*10 MW DER/DG is added to node 38*	*Difference (%)*
37-38	-3.56	-5.14	44.38
22-38	-8.29	-11.45	38.12
38-48	-8.12	3.56	-143.84
38-49	-1.88	3.51	-286.70
38-44	-1.69	6.47	-482.84

Line	*Active power flow at normal condition (MW))*	*Active power flow when 3*10 MW DER/DG is added to node 38*	*Difference (%)*
22-23	8.41	10.6	26.04
21-22	0.12	0.85	608.33
8-9	-175.08	-175.39	0.18
9-10	-17.75	-17.8	0.28
9-11	-24.25	-25.12	3.59
9-12	-14.91	-13.98	-6.24
9-13	-22.09	-22.32	1.04
9-55	5.75	5.62	-2.26

Finally, another 10 MW DG is added to the bus 38 of IEEE 57 bus test system and the results are presented in Table. IV and improvement of voltage profile is plotted in Fig. 6.

After the prevailing case another line contingency has been considered. The line connected with node 8 and node 9 is deleted and the comparison in voltage profile is observed in Fig. 7. The change in active power flow is obtained in the Table. V.

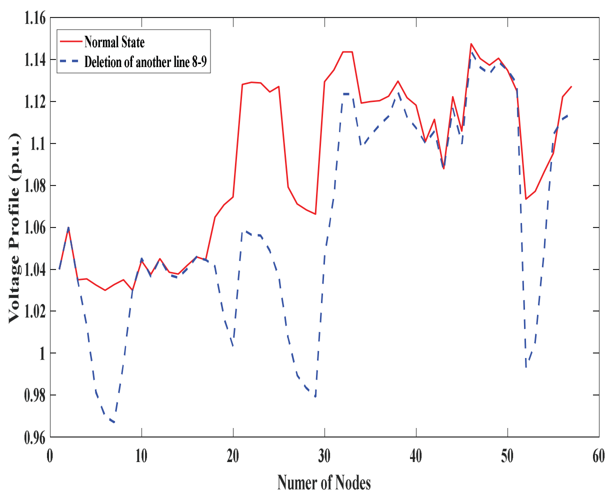

Fig. 7. Comparison of Voltage Profile before and after deletion of another line 8-9 in IEEE 57 bus test system

TABLE V. COMPARISON OF ACTIVE POWER FLOW AT NORMAL STATE AND WHEN ANOTHER LINE 8-9 IS ALSO REMOVED FROM IEEE 57 BUS TEST SYSTEM

Line	*Active power flow at normal condition (MW)*	*Active power flow when another line 8-9 is also removed*	*Difference (%)*
37-38	-3.56	-4.09	14.89
22-38	-8.29	-9.35	12.79
38-48	-8.12	-4.23	-47.91
38-49	-1.88	-0.08	-95.74
38-44	-1.69	1.03	-160.95
22-23	8.41	9.14	8.68
21-22	0.12	-0.2	-266.67
9-10	-17.75	7.74	-143.61
9-11	-24.25	20.89	-186.14
9-12	-14.91	6.9	-146.28
9-13	-22.09	20.79	-194.11
9-55	-5.75	57.69	-1103.3

Now another DG of 30 MW is added to the node 9 after deletion of two lines 38-22 and 8-9 one after another sequentially. In the previous case total 30 MW DG is added to the node 38 and the improvement in the voltage profile is observed. Lastly, another 30 MW DG is added to the node 9 and the improvement in voltage profile is plotted in the Fig. 8. The change in active power flow is presented in Table. VI.

TABLE VI. COMPARISON OF ACTIVE POWER FLOW AT NORMAL STATE AND WHEN 30 MW DER/DG IS ADDED TO NODE 9

Line	*Active power flow at normal condition (MW)*	*Active power flow when 30 MW DER/DG is added to node 9*	*Difference (%)*
37-38	-3.56	-4.09	14.89
22-38	-8.29	-9.35	12.79
38-48	-8.12	-4.23	-47.91
38-49	-1.88	-0.08	-95.74
38-44	-1.69	1.03	-160.95
22-23	8.41	9.14	8.68
21-22	0.12	-0.2	-266.67
8-9	-175.08	-181.9	3.90
9-10	-17.75	-13.13	-26.03
9-11	-24.25	-18.1	-25.36
9-12	-14.91	-9.73	-34.74
9-13	-22.09	-15.54	-29.65
9-55	5.75	6.23	8.35

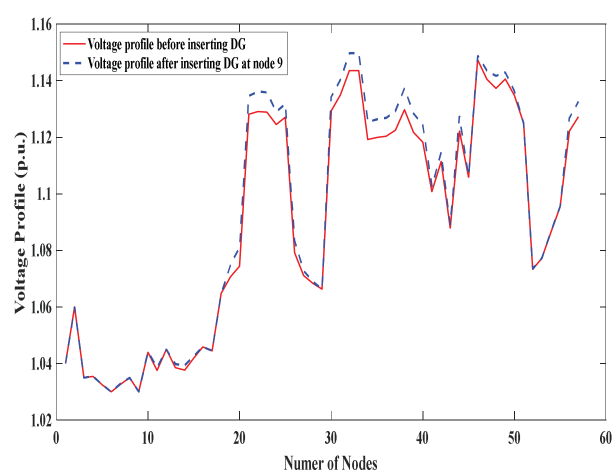

Fig. 8. Comparison of Voltage Profile before and after inserting another DG of 30 MW at the node 9 in IEEE 57 bus test system

So from the above mentioned results it can be concluded that incorporating DGs in the power network can enhance the resiliency of the network to withstand high impact low frequency events.

VII. Conclusion

In this paper a framework for the analysis of resiliency has been constructed by using graph theory. Analysis based on betweenness centrality and minimum spanning tree (using Kruskal's algorithm) and Newton Raphson method have been done to assess the resiliency of the network. Simulations and experiments have been conducted on IEEE 57 bus system. The results show that maximum disturbances have been found in case of a transmission line disconnected especially which carries more active power than the rest of the lines associated with the critical node. It has been also found same line shows maximum deflection of active power flow when extra distributed energy resources or DGs have been incorporated to the system. As a measure of improving resiliency the most critical lines should be prioritized and backed up by suitable DGs.

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