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Enhancement of transmission efficiency of power system in presence of sensitivity factor based optimally located renewable generating sources

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Abstract: As the power system is undergoing major structural and functional changes in past few years and the demand for electrical power is growing rapidly, the transmission system is pushed to operate closer to its limit. Also the losses in the transmission system are increasing with increasing power demand. As a result of this the power system is operating at lower efficiencies and hence there is a need for its improvement. The advancement in FACTS and integration of renewable generating sources into the power system has opened many options for improving transmission efficiency. In this paper effect of increasing load on transmission efficiency is discussed, also the use of renewable generating sources particularly solar and wind distributed generations (DG) to improve the same is discussed. Sensitivity factor approach is used to find the suitable location for placement of distributed generation. The results are demonstrated on IEEE 14 bus system.

Keywords: Transmission efficiency, Photovoltaic DG, Wind DG, sensitivity factor

1. Introduction

The electrical power system network is becoming highly integrated and complicated because of the increased power demand and deregulation in recent years. The power system is subdivided into three parts; generation where the electricity is generated, distribution where the power is supplied to end users and the transmission lines are used to transfer the power generated in the generating stations to load centers reliably and securely. Transmission lines are designed to operate with high-voltage electricity, in the range of several thousand volts to tens of thousands of volts. Even though they operate at higher voltage ranges, they are not hundred percent efficient. Nearly 8 to 10% of generated power is wasted in transmission lines which make the operation of whole power system less efficient [1].

In a transmission system, the power received at the receiving end is always less than the power sent from the sending end because of losses in the transmission line resistance. The transmission efficiency is the ratio of the receiving end power to the sending end power. Increasing power demand increases the losses in the transmission lines and reduces the efficiency [2]. The losses the transmission lines increase exponentially as lines become heavily loaded. Shutting down the small value of load during peak hour can lower the line losses by a much larger amount. Usually transmission line conductors are made up of pure aluminum or copper, both of which have low resistance for flow of current.

There are three parameters that contribute to conductor losses. The first one is the quality of the connections at both the end of the conductors. This is because corroded connectors or twisted wires result in arcing of current and wastes power in the form of heat. The second one is the dimension of the conductor relative to the current it carries. This is because of size of the conductor changes the resistance of the line and hence the transmission line losses. Sometimes it is required to change out the wires or re-conductor present lines to increase their capacity and reduce losses. This option is somewhat expensive and time consuming. The third factor is the voltage at which the transmission lines operate. Operating voltage has significant effect on losses by reducing the strength of current required to transmit power to customers. To have high voltage on a line requires new transformers to be installed. Operating lines with high voltage also necessitate taller poles and the costs involved in installing new poles are very large. Also installation of underground cable for high-voltage lines is more expensive than overhead line construction and is usually limited for short distances and for flat terrain.

Other than these more compact, scalable and simple new power flow control devices can also be used to improve efficiency of transmission system. Distributed series reactors (DSR) developed by Smart Wire Grid [3] can increase line impedance over demand by providing magnetizing inductance of one-turn transformer which is the main component in this device. Many DSRs are installed in high voltage lines [4]. Compact Dynamic Phase Angle Regulators (CD-PAR) developed by Varentec Inc, are series compensating devices consisting of power converter integrated with a transformer [5]. These can provide smooth and continuous control of active and reactive power flows through the line by controlling the angle and amplitude of injected voltage [6]. Transformer less Unified Power Flow Controller, developed by Michigan State University is another modified device from UPFC consisting of multilevel inverters to overcome the need of transformers. This makes the device more compact and less costly. This device controls the flow of power through the line so as to enhance the transmission efficiency [7]. The use of distributed generation such as solar photovoltaic and wind reduce system losses greatly if planned appropriately. Distributed generation helps by facilitating a source of power near the loads, thereby reducing the need for power transmission from remote power stations [8].

In this paper, an approach is proposed for optimal placement of solar and wind DGs of rated power at suitable load bus selected based upon the sensitivity factor so as to reduce the transmission losses and to improve the transmission efficiency.

2. Method

Transmission efficiency of a system can be enhanced with distributed energy generation (DG) by reducing line losses. The distributed generation includes nonconventional energy resources such as solar, wind, biomass and hydro power. These generation units are usually installed at the load points based upon the availability of resources and these are utilized for local needs. These generations can become alternate option for the construction of new transmission lines to cater the increasing power demand. In this paper use of solar and wind generations to enhance the transmission efficiency of a system are demonstrated.

2.1 Modeling of Photovoltaic (PV) DG

The photovoltaic systems are either connected to grid or operate as standalone. The electric current produced from PV cell is direct one. Therefore the electric power generated by PV cells is always DC; the same should be converted into AC for grid connectivity. Various topologies of inverters have been used to convert DC power from PV system into AC which also takes care of voltage and frequency match. In this study PV-DG is modeled as power generator [9] at load buses whose output varies with solar irradiance. The output power from PV system is given be equation (1)

$$P_{pv} = \begin{cases} P_{pvr} \times \left(\frac{G}{G_0}\right) & 0 \leq G \leq G_0 \\ P_{pvr} & G_0 \leq G \end{cases} \quad (1)$$

Here P_{pvr} is the rated output power of PV system at standard conditions (solar radiation=1000 W/m^2 and temperature=25° C). Also G and G_0 are the solar radiation (W/m^2) for the selected location and rated radiation on earth's surface (1000 W/m^2) respectively.

2.2 Wind Generation (WG) modeling

The wind generator produces AC power and can be connected directly to grid at medium or high voltage levels. In this paper WG is modeled as power generator [10], at load buses whose output varies with variation in wind speed. The output power from WG is given by equation (2)

$$P_w = \begin{cases} 0 & 0 \leq V \leq V_{ci} \\ P_r \frac{V - V_{ci}}{V_r - V_{ci}} & V_{ci} \leq V \leq V_r \\ P_r & V_r \leq V \leq V_{co} \\ 0 & V_{co} \leq V \end{cases} \quad (2)$$

Here V is the wind speed, V_{ci} is the cut-in speed, V_{co} is the cut-out speed and V_r is the rated speed. P_r Represents the rated power output of WG.

The reactive power generated or absorbed by distributed generator is product of tangent of power factor angle and real power output. Usually DGs absorb the reactive power while operating in lagging power factor mode whereas export reactive power during leading power factor mode. The reactive power absorbed or generated by DGs is zero if the operating power factor is unity.

2.3 Sensitivity factor for location of DGs

The solar photovoltaic DG and wind DG can generate the power in large capacity and can be located in all locations. But the uses of these DGs are limited by few important issues. Solar PV DG is intermittent source available during sunny days only and power from wind DG is available only when wind speed is more than its cut in speed. Also the number of DG with inappropriate size and at improper locations leads to reverse flow of power as well as increased system losses. It also results in uneconomical operation of system.

This problem of deciding appropriate size of DG at optimal location to have less system losses [11] is addressed in this paper by finding real power loss reduction sensitivity factor (PLRSF) given by equation (3).

$$PLRSF = \frac{P_{loss\ with\ DG} - P_{loss\ base}}{P_{DGi}} \quad (3)$$

Here, P_{DGi} is the size of the DG placed at load bus i, P_(loss base) is the initial power losses in the system, P_(loss with DG) is the power loss after placing DG. If the PLRSF value is expected to be negative always as the system losses are reduced after placement of DG, else the DG integration is not preferred. Therefore, the bus having highest negative PLRSF value is selected as optimal location for DG placement.

3. Case study

In this study IEEE 14 bus system shown in figure 1 is considered as test system for demonstration of proposed approach. It consists of three PV buses and nine load buses along with two transformers and one shunt capacitor.

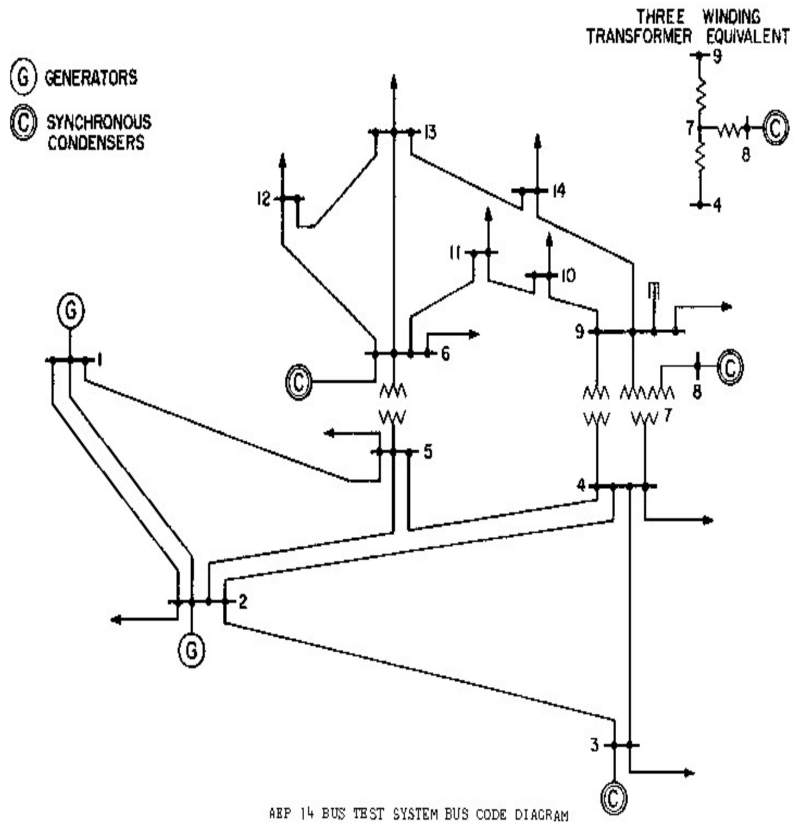

***Figure 1**: IEEE 14 bus power system*

3.1 Load profile of the system over a day

In order to determine transmission efficiency of test system under different loading conditions over a period of 24 hours, a sample load duration curve shown in figure 2 is considered. Even though the base case load is 259MW, over a period of 24 hours the load on the system varies from 220MW to 280MW which is nearly 70% to 108% of base case. 105% of base load is considered as peak load for analysis which is occurring at 12th hour even though the load at 20th hour is more that 108% which is rare option in real time operation of power system hence is not considered for analysis.

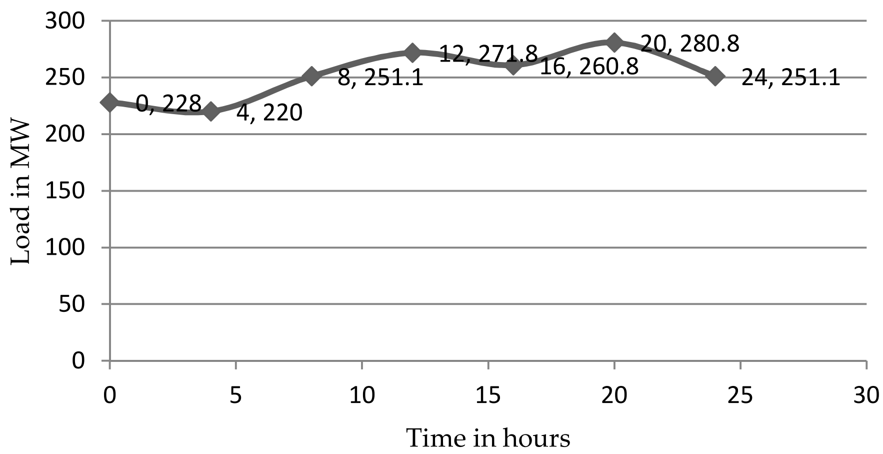

Figure 2: Daily load duration curve

3.2 Solar DG considerations

The rated power of solar DG is considered as 20MW as case (a) and 30MW as case (b) at rated irradiance of 1000 W/m2. The sample data of variation of solar irradiance in W/m2 over a period of 24 hours is as shown in figure 3.

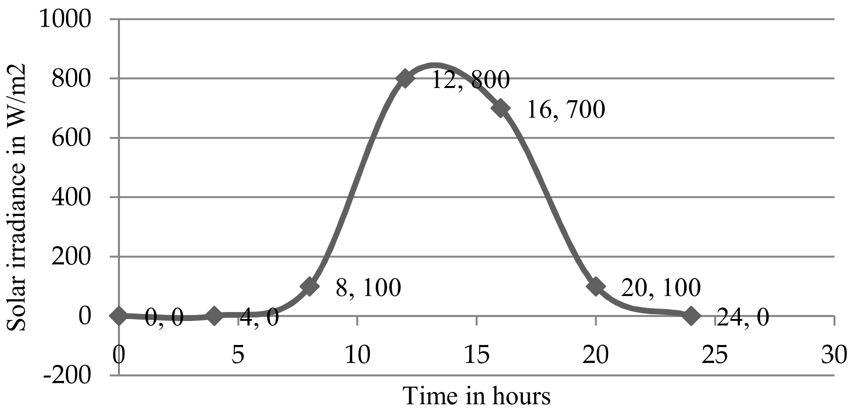

Figure 3: Sample data of solar irradiance over period of 24 hours

The real power output power from solar DG over a period of 24 hours as per the figure 5, is calculated using equation (1) are tabulated in table 1. The reactive power is calculated by taking product of active power and tangent of power factor angle. Three values of power factors considered are 0.95lag, unity and 0.95 lead.

Table 1: Solar DG output over 24 hours

Time in hours	**Solar irradiance W/m2**	**Case (a) with 20MW rated power**				**Case (b) with 30MW rated power**			
		Real power output in MW	**Reactive power output in MVAR**			**Real power output in MW**	**Reactive power output in MVAR**		
			pf= 1	**pf= 0.95 (lag)**	**pf=0.95 (lead)**		**pf= 1**	**pf= 0.95 (lag)**	pf=0.95 (lead)
0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
8	100	2	0	0.6572	-0.6572	3	0	0.9858	-0.9858
12	**800**	**16**	**0**	**5.248**	**-5.248**	**24**	**0**	**7.8864**	**-7.8864**
16	700	14	0	4.6004	-4.60	21	0	6.9006	-6.9006
20	100	10	0	0.6572	-0.6572	3	0	0.9858	-0.9858
24	0	0	0	0	0	0	0	0	0

3.3 Wind DG considerations

The rated power output of wind DG is considered as 20MW as case (a) and 30MW as case (b), at rated wind speed of 9.73m/sec. Cut-in speed of wind and cut-out speed are considered as 5.56m/sec and 13.9m/sec respectively. The sample data of variation of wind speed in km/hr over period of 24 hours is shown in figure 4.

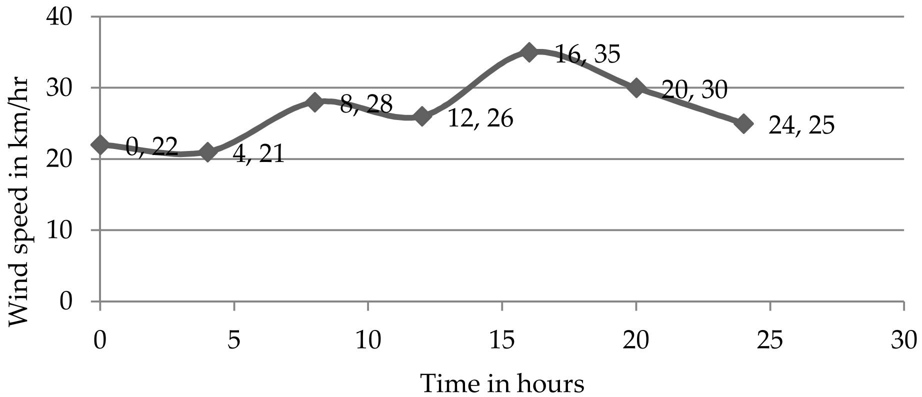

Figure 4: Sample data of wind speed over a period of 24 hours

The real power output from wind DG over a period of 24 hours as per the figure 4, is calculated using equation (2) are tabulated in table 2. The reactive power is also tabulated for 0.95 lag, unity and 0.95leading power factors.

Table 2: Output power from wind DG

Time in hours	Wind speed in m/sec	Case (a) with 20MW rated power				Case (b) with 30MW rated power			
		Real power output in MW	Reactive power output in MVAR			Real power output in MW	Reactive power output in MVAR		
			pf= 1	pf= 0.95 (lag)	pf=0.95 (lead)		pf= 1	pf= 0.95 (lag)	pf=0.95 (lead)
0	6.11	2.67	0	0.8642	-0.8642	3.95	0	1.3144	-1.3144
4	5.838	1.33	0	0.437	-0.437	1.998	0	0.6565	-0.6565
8	7.784	10.67	0	3.499	-3.499	15.99	0	5.2576	-5.2576
12	7.228	8	0	2.6288	-2.6288	11.99	0	3.9432	-3.9432
16	9.73	20	0	6.572	-6.572	29.98	0	9.858	-9.858
20	8.34	13.33	0	4.3769	-4.3769	19.96	0	6.572	-6.572
24	6.95	6.67	0	2.188	-2.188	9.99	0	3.286	-3.286

4. Results and Discussion

The power flow analysis is carried out on IEEE 14 bus system for varying load conditions to obtain the transmission losses so as to obtain the efficiency. It is observed from the table 3 that transmission efficiency decreases as loading on the system increases. From base case to a peak load condition nearly 1% reduction in efficiency is observed.

Table 3: Transmission efficiency for varying load conditions

Sl.No	% Load	Load in MW	Power Generation in MW	Percentage efficiency
1	Base Case	259	272.593	95.013
2	103	266.77	281.352	94.82
3	105	271.950	287.125	94.72
4	108	279.72	295.830	94.5
5	110	284.9	301.652	94.44

The power flow analysis is carried out further to observe the efficiency in presence of line outages also. The results are tabulated in table 4. It is observed that transmission efficiencies during line outages are less than without outages. It is observed that transmission efficiency is minimum during outage of line 1 to 2

Table 4: Transmission efficiency during line outages

Line outage	% Efficiency	Line outage	% Efficiency
1-2	259/302.552*100=85.61	6-11	259/272.652*100=94.99
1-5	259/280.567*100=92.31	6-12	259/272.701*100=94.99
2-3	259/283.600*100=91.33	6-13	259/273.58*100=94.67
2-4	259/274.638*100=94.30	7-9	259/273.31*100=94.76
2-5	259/273.44*100=94.72	9-10	259/272.5*100=95.041
3-4	259/271.695*100=94.97	9-14	259/272.91*100=94.91
4-5	259/275.170*100=94.123	10-11	259/272.4*100=95.04
4-7	259/272.68*100=94.98	12-13	259/272.4*100=95.04
4-9	259/272.5*100=95.04	13-14	259/272.585*100=95.016
5-6	259/275.8*100=93.91	Without outage	259/273.5*100=95.05

4.1 Computation of PLRSF for all load buses:

As the transmission efficiency has to be enhanced at 12:00 hours the output power of the solar DG at this time is 16 MW (for case (a)) and that of wind DG is 8MW from table 1 and 2 respectively. To find optimal location these DGs, real power loss reduction sensitivity factor (PLRSF) is computed by placing DGs at all load buses for peak load condition at unity power factor and are tabulated in Table 4. It is observed that bus number 14 is the suitable location for placement of DG as it results in least power losses with larger PLRSF.

Table 5: Real power loss reduction sensitivity factor (PLRSF) with DG at load buses

Load Bus number	With 20MW rated solar DG load bus			With 20MW rated wind DG load bus		
	Power loss in MW	PLRSF	Rank	Power loss in MW	PLRSF	Rank
4	13.324	-0.1215	5	14.219	-0.1311	4
5	13.613	-0.1034	8	14.366	-0.1128	8
9	13.299	-0.1231	3	14.221	-0.1309	5
10	13.288	-0.1238	2	14.201	-0.1334	3
11	13.478	-0.1119	6	14.265	-0.1254	7
12	13.499	-0.1106	7	14.244	-0.1280	6
13	13.319	-0.1218	4	14.183	-0.1356	2
14	13.033	-0.1397	1	14.036	-0.1540	1

Table 6: Transmission efficiency at peak load with and without DG

Operating power factor	Transmission Efficiency without DG	Transmission Efficiency with DG at bus number 14			
		Solar DG of rated power		Wind DG of rated power	
		20MW	30MW	20MW	30MW
Unity	94.68%	95.42%	95.69%	95.08%	95.19%
0.95 lag		95.37%	95.62%	95.049%	95.205%
0.95 lead		95.45%	95.73%	95.118%	95.28%

It is observed from the table 6 that transmission efficiency is more with DG compared to that of without DG. Also efficiency is more in case of leading power factor mode as DGs export reactive power to the grid. Therefore by locating the appropriate size DG at suitable load bus can enhance the transmission efficiency of a system.

5. Conclusion

As the power system is undergoing major structural and functional changes in recent years due to increased power demand, there is always need for upgrading the power system performance. Transmission efficiency is one such performance of power system, addressed in this paper. Use of DGs to improve the transmission efficiency is discussed in this paper. As the power system is moving from centralized generation to distributed generation these days, the advantage of having DGs in the system to enhance efficiency is a novel approach compared to the one by using FACTS or any other compensating devices . Solar DG and wind DG of different rated powers are placed at suitable load bus based upon the sensitivity factor to minimize the transmission losses and hence enhance the transmission efficiency. The impact of increasing the number of DGs and the size of DGs on efficiency is next research question to be addressed.

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