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Optimal Operation of PV Integrated Smart Distribution Feeder

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Abstract: Solar photovoltaic (PV) is the most widely used renewable energy source in the present time due to its cost-effective and eco-friendly advantages. It is also one of the important components of smart grid. A smart grid cannot achieve completeness unless this renewable energy source is integrated in it. However, integration of solar PV into distribution system poses various challenges like reverse power flow, voltage variation, harmonics etc. Moreover the distribution grids are not designed to accommodate such sources of energy. In order to overcome these challenges and achieve smart grid goals, Solar PVs have to be controlled in synchronization with other components of the distribution grid so that the optimal operation of the network can be achieved. For the optimal operation of a smart power system accurate decision making algorithm is required, which should not only be fast enough but able to give the decision under various nonhomogeneous conditions. This paper presents the convex optimization technique for a solar PV integrated network, in order to achieve the smart distribution grid goals such as the optimal flow of power, reduction in losses and improvement in voltage profile.

Keywords: Convex optimization, optimal power flow, solar PV integrated distribution system, interior point method

1. INTRODUCTION

The planning, operation and management of modern electrical grids have become more and more difficult due to the challenges posed by the integration of intermittent renewable energy sources and variable load demands. For the optimal operation of a smart power system accurate decision making algorithm is required, which should not only be fast enough but able to give the decision under various nonhomogeneous conditions. In order to achieve the optimal operation of a power system, depending upon the nature of the problem, an optimal power flow (OPF) solution is required. The aim of optimal power flow analysis is to find the settings of the given power system which optimizes its performance by minimizing the fuel cost, minimizing the power losses and improving the voltage profile, though optimal settings of the control variables and satisfying various distribution system operating constraints[1-5]. Selection of a perfect solver for OPF solution is a tough task. A suboptimal solver requires large volume of empirical tunings and iterations and does not guarantee the required accuracy. The research in the field of optimal power flow (OPF) analysis has got tremendous impetus in last decades. Convex optimization method is one of the most promising standard methods to avoid these shortcomings. This paper presents the convex optimization technique for a solar PV integrated network, the convex optimization technique utilizes interior-point methods, a class of algorithms, to solve the convex optimization problem very reliably and efficiently. The developed smart distribution grid model is used to illustrate the effectiveness of the proposed method .The test results show that the proposed method is effective and has a certain practicality. The paper is organizes as follows Section II presents the modeling of smart distribution grid; Section III presents the basics of convex optimization; Section IV presents theoptimal power flow algorithm; Formulation of problem is given in Section V; Results and discussion presented in section VI; Section VII concludes with the findings and observations made.

2. MODELING OF SMART DISTRIBUTION

The smart grid distribution system with solar PV integration is modeled as shown in the figure 1. Loads are fed from an 11KV grid through a transformer of rating 1.5 MVA, 11/0.433 KV. Laterals are feeding the loads of varying nature in the area. Solar PVs are connected at the bus nos. 5 and 16, their rating details are given in table 1. The distribution cable data are given in table 2.

TABLE 1: PARAMETERS OF SOLAR PV MODULES

S. No.	PV panel (Watt/panel)	280
1	PV panels in series	11
2	PV panels in parallel	161
3	Total No. of panels	1771
4	Volts , dc	400
5	KW, dc	500
6	Amp, dc	1240
7	Inverter, kva	600
8	Inverter, Amp	800
9	Inverter, output voltage (volts)	433

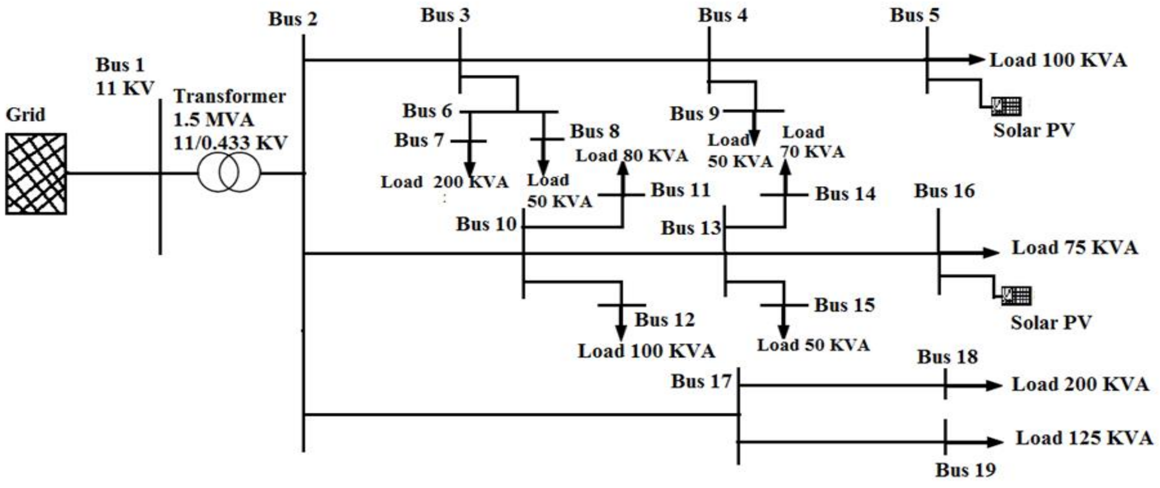


Figure 1: Distribution Grid with Solar PV

TABLE 2: CABLE INPUT DATA (OHMS OR MHOS / 1000 FT. PER CONDUCTOR)

Cable ID	**From Bus**	**To Bus**	**Size (mm^2)**	**Length (ft.)**	**R1**	**X1**	**R0**	**X0**
Cable 1	Bus2	Bus3	400	60	0.018635	0.025969	0.119773	0.012192
Cable 2	Bus3	Bus4	400	50	0.018635	0.025969	0.119773	0.12192
Cable 3	Bus4	Bus5	400	125	0.018635	0.025969	0.119773	0.12192
Cable 4	Bus3	Bus6	300	200	0.023286	0.026335	0.172391	0.012802
Cable 5	Bus6	Bus 7	300	60	0.023286	0.026335	0.172391	0.012802
Cable 6	Bus6	Bus 8	35	35	0.19434	0.028164	1.011964	0.017678
Cable 7	Bus4	Bus 9	35	250	0.19434	0.028164	1.011964	0.017678
Cable 8	Bus2	Bus 10	400	100	0.018635	0.025969	0.119773	0.012192
Cable 9	Bus 11	Bus 10	35	180	0.19434	0.028164	1.011964	0.017678
Cable 10	Bus 10	Bus 12	70	250	0.09919	0.027432	0.515139	0.01585
Cable 11	Bus 10	Bus13	400	50	0.018635	0.025969	0.119773	0.012192
Cable 12	Bus 14	Bus13	35	100	0.19434	0.028164	1.011964	0.017678
Cable 13	Bus13	Bus 15	35	75	0.19434	0.028164	1.011964	0.017678
Cable 14	Bus13	Bus 16	400	130	0.018635	0.025969	0.119773	0.012192
Cable 15	Bus2	Bus 17	400	200	0.018635	0.025969	0.119773	0.012192
Cable 16	Bus 17	Bus 18	300	100	0.023286	0.026335	0.172391	0.012802
Cable 17	Bus 17	Bus 19	70	200	0.09919	0.027432	0.515139	0.01585

3. CONVEX OPTIMIZATION

In this section, we deal with the class of optimization problem called convex optimization problem [6]. To minimize a function f(x)

Subject to gi(x) ≤ai, i = 1, . . . ,m.

Here the vector $x = (x_1, \ldots, x_n)$ is the optimization variable of the problem, the function $f : \mathbf{R}^n \rightarrow \mathbf{R}$ is the objective function, the functions $g_i: \mathbf{R}^n \rightarrow \mathbf{R}$, i = 1, . . .,m, are the inequality constraint functions, and the constants $a_1, \ldots, a_m$ are the limits for the constraints. In such optimization, the objective and constraint functions are convex and satisfy the given (1) inequality

$$g_i(\sigma x + \delta y) \leq \sigma g_i(x) + \delta g_i(y) \qquad (1)$$

for all x, y $\in \mathbf{R}^n$ and all σ, δ $\in \mathbf{R}$ with $\sigma + \delta = 1$, $\sigma \geq 0$, $\delta \geq 0$.

4. OPTIMAL POWER FLOW ALGORITHM

The optimal power flow (OPF) analysis is the most useful tool in power system operation and planning. Generally, the OPF problem can be formulated as follows [7 – 12]:

$$\text{Min } J = f(x,u) \qquad (2)$$

Subject to

- Equality constraints:

$$P(x,u) = 0 \text{ and} \qquad (3)$$
$$Q(x,u) = 0 \qquad (4)$$

- Inequality constraints:

$$u_{min} \leq u \leq u_{max} \qquad (5)$$
$$y(x,u)_{min} \leq y(x,u) \leq y(x,u)_{max} \qquad (6)$$

Where

x Bus voltage vector, called state variable set;
u System control vector, called control variable set;
f Objective functions, expressed in terms of x and u;
y System output vector, a variable set typically including line flows, etc., as a function of x and u;
P Real power, expressed in terms of x and u;
Q Reactive power, expressed in terms of x and u;

The specified objective function to be minimized or optimized is represented by (2). System power balance equations to be solved are represented by (3-4). The control upper and lower limits are given by (5) while the upper and lower limit for output variables is given in (6). The equality and inequality constraints are as below

- Power flow equations
- Generation / load balance
- Branch flow limits (MW, MVAr, MVA)
- Bus voltage limits
- Limits on all control variables

1)

5. PROBLEM FORMULATION

In [13] an optimization algorithm is proposed which provides the solution based on projective transformations of points variables and corresponding optimization over an inscribed sphere. The algorithm for generation of primal and dual solutions of economic significance with objective values converging to a common optimal primal and dual value is presented in [14]. A barrier function was used, which was a combination of original objective function and weighted sum of functions with positive singularity at the boundary. As the weight assigned to the singularities approaches zero, the minimum of the barrier function approaches the minimum of the original constrained problem.

Objective function for the optimal power flow is given as

$$J = f(x) = \sum_{K=1}^{N} fpvk(Ppvk) + floss.\delta \sum_{k=1}^{N} Plk + fgc(Pgc) \qquad (7)$$

Where
$fgc(Pgc)$: Grid costing function
$fpv(Ppv)$: PV unit costing function
Plk: Power loss in branch k
δ : weighting factor for power loss

Objective function for the optimal power flow using interior point method with barrier function is given as

$$fip(x) = f(x) - \mu \textstyle\sum_{k=1}^{N} \ln xk \qquad (8)$$

Where μ is a positive parameter and x is the vector for power flow variables.

The convex optimization utilizes interior-point methods, a class of algorithms used to solve the convex optimization problem. The interior point algorithm as a solution for OPF is given in various literatures [15-18]. It is presented below for (7) and (8), to obtain the optimal operation of the solar PV integrated distribution system.

(1) Initialize the power flow variables and get variable initial point x_0
(2) Compute the next point x_1 for the power flow residual variable and check tolerance stop if the required tolerance is met.

(3) Initialize the barrier parameter and nonlinear terms
(4) Solve for the correction vector
(5) Update the variables
(6) Check the tolerance otherwise go to step 2

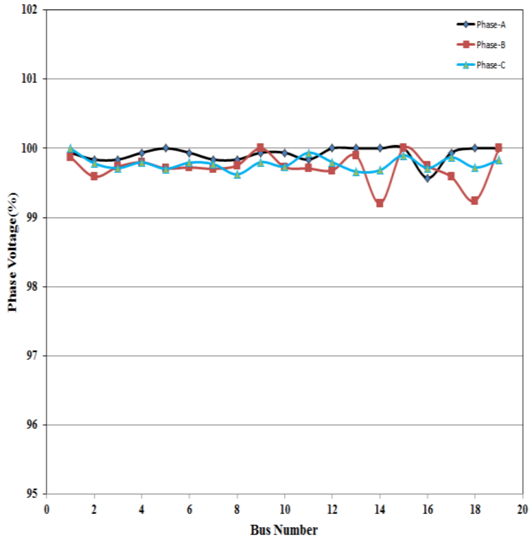
6. RESULTS AND DISCUSSIONS

This section presents the results for the optimal power analysis using convex optimization and interior point algorithm. The objectives and simulation parameters weights are given in table 3.

TABLE 3: OBJECTIVES AND SIMULATION PARAMETERS

Minimize Real Power Losses	100 %
Minimize Reactive Power Losses	100 %
Minimize Fuel Cost	100 %
Barrier Factor	0.0000001
Bus Voltage Constraint	97 -103%

Results for the optimal operation of distribution system incorporating Solar PVs at the bus no. 5 and 16 are presented in table nos. 4 & 5. The OPF results in which the generation and loads of particular buses are shown in table no. 4. While table no. 5 presents the OPF results in which the optimal values of various load flow data are given. The negative values correspond to the reverse direction of power at given buses. Fig. 2 presents the operation of network before and after optimization process.



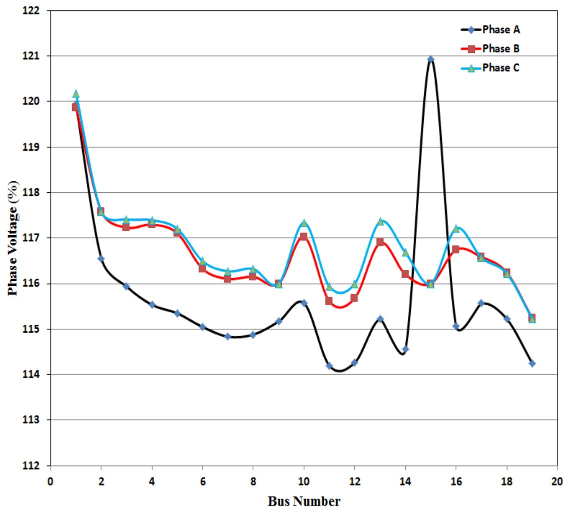


Fig.2 Variation in voltage at different bused (a) Before regulator operation (b) After optimized regulator operation

TABLE 4: PARAMETERS OF OPTIMAL POWER FLOW AT GENERATION SIDE

Bus	**Voltage**		**Generation**		**Load**	
No.	**KV (Stated)**	**% (Found)**	**MW**	**Mvar**	**MW**	**Mvar**
1	11	97.11	0	0	0	0
2	0.433	94.90	0	0	0	0
3	0.433	94.80	0	0	0	0
4	0.433	94.91	0	0	0	0
5	0.433	95.30	0.444	0	0.077	-0.048
6	0.433	93.88	0	0	0	0
7	0.433	93.66	0	0	0.162	0.026
8	0.433	93.71	0	0	0.04	0.007
9	0.433	93.69	0	0	0.04	0.007
10	0.433	94.76	0	0	0	0
11	0.433	93.36	0	0	0.065	0.011
12	0.433	93.43	0	0	0.081	0.013
13	0.433	94.84	0	0	0	0
14	0.433	94.16	0	0	0.057	0.009
15	0.433	94.48	0	0	0.041	0.006
16	0.433	95.29	0.444	0	0.058	-0.036
17	0.433	93.91	0	0	0	0
18	0.433	93.57	0	0	0.149	-0.092
19	0.433	92.57	0	0	0.100	0.017

TABLE 5 PARAMETERS OF OPTIMAL POWER FLOW AT LOAD SIDE

Bus No.	**Optimal Load Flow**		
	MW	**Mvar**	**Amp**
1	0.002	-0.554	778.2
2	0	0.567	30.6
	0.119	-0.204	331.9
	0.137	-0.191	330.4
	-0.251	-0.155	419.3
3	-0.118	0.204	331.9
	0.324	-0.076	446.7
	-0.202	-0.126	338.4
4	-0.323	0.076	466.7
	0.366	-0.048	517.1
	-0.04	-0.025	67.7
5	-0.365	0.05	517.1
6	0.204	0.127	338.4
	-0.162	-0.1	270.7
	-0.04	-0.025	67.7
7	0.162	0.101	270.7
8	0.041	0.025	67.7
9	0.041	0.025	67.7
10	-0.065	-0.04	108.4
	-0.081	-0.05	135.5
	0.285	-0.099	424.9
	-0.137	0.191	330.4
11	0.066	0.04	108.4
12	0.082	0.05	135.5
13	-0.285	0.1	424.9
	-0.57	-0.035	94.6
	-0.41	-0.025	67.5
	0.386	-0.036	542.1
14	0.057	0.035	94.6
15	0.041	0.025	67.5
16	-0.384	0.039	542.1
17	-0.149	-0.092	249.5
	0.253	0.158	419.3
18	0.149	0.093	249.5
19	0.102	0.063	169.7

7. CONCLUSION

It is true that the modern grids are accommodating more and more renewable energy sources like solar PVs, Due to their cost-effective and eco-friendly advantages, but the optimal operation of grids is very difficult to achieve due to the varying nature of sources and loads, as the grids are moving towards smart grid era the operation optimization is a crucial need to achieve the grid objectives. PVs have to be controlled in coordinated way with other equipments such as tap changers, voltage regulators, compensators with in the distribution network. In this paper we have obtained the optimal values of various electrical quantities like voltage, current, active power, reactive power, power at various buses of a smart distribution system. Above method can be used to obtain the optimal parameters on line for any number of buses and helps the operator to manage the smart power system effectively.

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