FOREX Publication
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International Journal of Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 3 | Pages 711-719 | e-ISSN: 2347-470X

Optimal Power Flow for Distribution System using Gradient-Based Optimizer

Sanket Raval[1] and Thangadurai Natarajan[2]

[1]*Research Scholar, Department of Electrical Engineering, Faculty of Engineering and Technology, Sankalchand Patel University, Visnagar, Gujarat, India, scraval93@gmail.com*

[2]*Associate Director and Professor, Centre for Research and Innovation, Sankalchand Patel University, Visnagar, Gujarat, India*

***Correspondence:** Sanket Raval; scraval93@gmail.com

ABSTRACT- In the distribution network, DG penetration increases prominently, and has altered the nature of the distribution network into an active and passive network. DISCOMs/DSOs are incorporating all kinds of DGs, including non-renewables and renewables now a day. If DGs are planned and controlled adequately, then it improves voltage deviation, reduces active power loss, and leads to the economic operation of the active distribution network. Efficient operation of the distribution network can be achieved by solving optimal power flow. In this work, optimal power flow (OPF) for a modified IEEE-69 bus distribution network with DGs is formulated and solved using Gradient Based Optimizer (GBO) in MATLAB 2021a. OPF is solved with objectives to minimize fuel cost, voltage profile improvement, and active power losses. The performance of GBO is compared with other state of art algorithms (PSO, ABC, GWO, and JANA). Performance analysis proves the efficacy and capability to solve real-world problems of GBO over other state of art algorithms.

Keywords: Active power loss, Distribution network, Gradient-based optimizer, Optimal power flow, Fuel cost, Voltage deviation.

ARTICLE INFORMATION

Author(s): Sanket Raval and Thangadurai Natarajan;

Received: 17/11/2022; **Accepted**: 01/08/2023; **Published**: 10/08/2023;

e-ISSN: 2347-470X;

Paper Id: IJEER220932;

Citation: 10.37391/IJEER.110311

Webpage-link:

https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110311.html

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1. INTRODUCTION

In 21st century, electricity is the prime requirement of any individual. From early stage, generation of electricity is from mostly from thermal, hydro and nuclear power plant. Thermal and nuclear power plant has disadvantage of creating pollution and safety issue, whereas hydro power plant has very high capital cost. There were many studies conducted to reduce emission, active power loss, total cost, and voltage deviation in transmission systems. These studies lead to formulation of optimal power flow and use of optimization techniques to get optimal values of control variables.

Now, it has been necessary to include renewable energy sources in the distribution system to reduce carbon emission. Generalized term for smaller capacity of energy sources at distribution level is called distributed generation (DGs) which includes renewable energy sources as solar photovoltaics (PV), small wind turbines (WT), mini hydro plants (MHP) and non-renewable sources as fuel cells (FC), micro turbines (MT) and diesel electric generators (DEG). Generally, DG which has converter circuits to control active power and voltage independently, DG is modelled as PV bus and when converter circuits is used to control active and reactive power independently, DG is modelled as PQ bus [1]. If DGs are planned and controlled optimally, operation of distribution system can be optimized in terms of reduction in active power loss, cost and voltage fluctuations [2]. To achieve optimal operation, optimal power flow (OPF) study for distribution system needs to be done.

OPF is a nonlinear, convex, and static optimization problem with continuous and discrete control variables [3]. Studies had been done on OPF for distribution system using linear programming, quadratic programming and dynamic programming [4-5]. Classical optimization fails to solve nonlinear and convex problems and stuck at local optima [5]. Meta-heuristic techniques are not problem-dependent techniques avoid local optima problems [6].

Recently many populations-based optimization techniques are applied to OPF problem such as genetic algorithm (GA) [7], particle swarm optimization (PSO) [8], gravitational search algorithm (GSA) [9]. In this work optimal power flow problem with DGs is formulated for modified IEEE-69 bus. Gradient-based optimizer (GBO) which is new meta-heuristic optimization technique is used to find optimal control variables. In [10] performance of GBO is evaluated for economic load dispatch problem. Electric vehicle charging station placement problem is also solved using GBO [11].

The contribution of this work is that problem formulation of this work takes care of renewable and non-renewable energy sources. Modified IEEE-69 bus system has renewable energy sources *i.e.*, solar PV and wind turbine and non-renewable energy sources *i.e.*, fuel cell and micro-turbine. It also includes

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the shunt var compensator. Main objective of problem formulation is to minimize fuel cost, power loss and voltage deviation. Performance of GBO over four state of art meta-heuristic algorithms i.e., PSO, ABC, GWO and JANA is compared in terms of statistical parameters and convergence rate.

In *section 2*, optimal power flow is formulated with equality and non-equality constraints. Gradient-based optimizer technique is explained in *section 3*. In *section 4*, the methodology to OPF using GBO is stated. Results of OPF for modified IEEE-69 bus with GBO and other state of art algorithms are presented in *section 4* with statistical analysis. In *section 5*, work is concluded with future scope of this study.

2. OPTIMAL POWER FLOW PROBLEM FOR DISTRIBUTION NETWORK

2.1 Formulation of Optimal Power Flow

Basically, OPF is formulated to minimize objective function by optimal values of control variables and constraints (equality and inequality both). Simplified version of OPF is stated below where F is the function which is to be minimized.

$$min\ F\ (x, y) \quad (1)$$

$$g(x, y) = 0 \quad (2)$$

Subject to

$$h(x, y) \leq 0 \quad (3)$$

where g is equality constraint and h is inequality constraint. *x* and *y* are control and dependent variables.

For distribution networks, control variable x includes active power output of DG with non-renewable sources (P_{DG}), slack bus voltage (V_0), voltage of PV bus (V_{PV}) and reactive power output of shunt Var compensator (Q_C). Dependent variable y includes active power transferred through slack bus (P_{gr}), load bus voltage including DGs which are modelled as PQ bus (V_L), reactive power output of DGs which are modelled as PV bus (Q_{DG}) and line flow (S_l).

2.2 Objective Function

To minimize generating cost, active power loss and voltage deviation at load buses simultaneously, multi-objective function is formulated as shown in *equation (4)*.

$$F = f_{gr}(P_{gr}) + \sum_{i=1}^{NR} f_i(P_{DGi}) + w_L \sum_{i=1}^{B} P_{Lossi} + w_V \sum_{i=1}^{L} |1 - V_i| \quad (4)$$

Where $\boldsymbol{f_{gr}(P_{gr})}$ is cost characteristics of active power transferred from slack bus, $\boldsymbol{f_i(P_{DGi})}$ is generating cost characteristics of DG (non-renewable) at i^{th} bus, $\boldsymbol{P_{Lossi}}$ is active power loss at i^{th} branch and V_i is voltage at i^{th} load bus. *NR*, *B* and *L* are number of non-renewable DG, number of branches and number of load buses respectively. $\boldsymbol{w_L}$ and $\boldsymbol{w_V}$ are weighting factor of active power loss and voltage deviation respectively.

2.3 Constraints

Objective function shown in *equation (4)* is solved subject to equality and non-equality constraints. Equality constraint includes power balance equation as shown in *equation (5)*.

$$\sum_{i=1}^{NR} \boldsymbol{P_{DGi}} + \sum_{i=1}^{R} \boldsymbol{P_{DGi}} + \boldsymbol{P_{gr}} = \sum_{i=1}^{L} \boldsymbol{P_{Li}} + \sum_{i=1}^{B} \boldsymbol{P_{Lossi}} \quad (5)$$

where R is number of renewable DG and $\boldsymbol{P_{Li}}$ is active load power at bus *i*. Inequality constraints are slack bus voltage (V_0) limit, PV bus voltage (V_{DG}) limit, load bus voltage (V_i) limit, DG reactive power (Q_{DG}) limit, branch power flow (S_i) limit and shunt Var compensator (Q_c) limits as shown in *equation (6)* to (11).

$$V\_0\^min \leq V\_0 \leq V\_0\^max \quad (6)$$

$$V\_DGi\^min \leq V\_DGi \leq V\_DGi\^max, i = 1, \ldots., PV \quad (7)$$

$$V\_i\^min \leq V\_i \leq V\_i\^max, i = 1, \ldots., L \quad (8)$$

$$Q\_DGi\^min \leq Q\_DGi \leq Q\_DGi\^max, i = 1, \ldots., PV \quad (9)$$

$$S\_i \leq S\_i\^max, i = 1, \ldots., B \quad (10)$$

$$Q\_Ci\^min \leq Q\_Ci \leq Q\_Ci\^max, i = 1, \ldots., C \quad (11)$$

Here PV and C are number of PV buses and number of shunt Var compensator respectively.

3. DG MODELING FOR OPF (Eq check)

In this section, cost characteristics of non-renewable sources and modeling of renewable sources are described.

3.1 Fuel Cell (FC)

Cost characteristics of fuel cell is denoted by f_{FC} [12],

$$f_{FC} = \frac{c_{FC} \times P_{FC}}{n_{FC}} \quad (12)$$

Here c_{FC}, P_{FC} and n_{FC} are fuel price ($/kW h), output power (kW) and fuel cell efficiency ($/h) respectively. Data of fuel cell are taken from [13].

3.2 Micro turbine (MT)

Cost characteristics of fuel cell is denoted by f_{MT},

$$f_{MT} = \frac{c_{MT} \times P_{MT}}{n_{MT}} \quad (13)$$

Here c_{MT}, P_{MT} and n_{MT} are fuel price ($/kW h), output power (kW) and micro turbine efficiency ($/h) respectively. Data from micro turbine is taken from [14].

3.3 Wind Turbine (WT)

Wind power (P_{wt}) output depends on wind speed and can be calculated by,

$$P_{wt} = \begin{cases} 0, & for\ v \leq v_{ci} \\ \frac{v^2 - v^2{}_{ci}}{v^2{}_{nom} - v^2{}_{ci}} \cdot P_{nom}, & for\ v_{ci} < v \leq v_{nom} \\ P_{nom}, & for\ v_{nom} < v \leq v_{co} \\ 0, & for\ v > v_{co} \end{cases} \quad (14)$$

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Here P_{nom}, v_{nom}, v_{ci} and v_{co} are rated power (kW), rated wind speed (m/s), cut-in wind speed (m/s) and cut out wind speed (m/s) of WT. Fcost for windfarm is always zero and they operate with maximum extracted power. WT data is taken from [15].

3.4 Solar Photovoltaic (PV)

The output power of PV is depends on solar radiation and temperature and type of PV panel. The Fcost of PV is also zero. Output power from PV can be calculated by [16],

$$P_{pv} = P_{stc} \cdot \frac{I_s}{1000}[1+\alpha(T_c - 250)] \quad (15)$$

Here Ptc and Is are maximum power output under strandard test condition (in watt) and solar radiation on PV panel surface (in watt/m²). $\boldsymbol{\alpha}$and T_c are temperature constant (in $^{\mathbf{0}}\boldsymbol{C}^{-\mathbf{1}}$) and PV panel temperature (in $^{\mathbf{0}}\boldsymbol{C}$). For this work SW 250 nano modules are used [17].

4. GRADIENT-BASED OPTIMIZER (GBO)

GBO is newly invented metaheuristic technique which balances exploration and exploitation process in optimization [18].

4.1 Gradient Search Rule (GSR)

The GSR gives random behavior in exploration. The *equation (16)* updates the current position.

$$Z1_n^m = z_n^m - randn \times \lambda_1 \times \frac{2\Delta z \times z_n^m}{z_w - z_b + \varpi} + rand \times \lambda_2 \times (z_b - z_n^m) \quad (16)$$

where

$$\lambda_1 = 2 \times rand \times \theta - \theta \quad (17)$$

$$\theta = \left|\tau \times sin\left(\frac{3\pi}{2} + sin\left(\tau \times \left(\frac{3\pi}{2}\right)\right)\right)\right| \quad (18)$$

$$\tau = \tau\_min + (\tau\_max - \tau\_min\ ) \times (1 - (m/M)^\wedge3\ )^\wedge2 \quad (19)$$

where $\boldsymbol{\tau_{min}}$ and $\boldsymbol{\tau_{max}}$ are 0.2 and 1.2, m is the iteration count, and M is the total iteration count. randn is normally distributed random number, and $\boldsymbol{\varpi}$ is number between 0 and 0.1. $\boldsymbol{\lambda_2}$is given by:

$$\lambda_2 = 2 \times rand \times \theta - \theta \quad (20)$$

$$\Delta z = rand(1{:}N) \times |step| \quad (21)$$

$$step = \frac{(z_b - z_{k1}^m) + \psi}{2} \quad (22)$$

$$\psi = 2 \times rand \times \left(\left|\frac{z_{k1}^m + z_{k2}^m + z_{k3}^m + z_{k4}^m}{4} - z_n^m\right|\right) \quad (23)$$

where rand(1:N) is a random number with N dimensions, k_1, k_2, k_3 and k_4 ($k_1 \neq k_2 \neq k_3 \neq k_4 \neq n$) are different integers randomly chosen from [1, N], step is step size.

By replacing best vector position zb with the current vector z_n^m *equation (16)*, the new vector $Z2_n^m$ can be generated as follows:

$$〖Z2〗\_n^\wedge m = z\_b - randn \times \lambda\_1 \times (2\Delta z \times z\_n^\wedge m)/(b\_n^\wedge m - c\_n^\wedge m + \varpi) + rand \times \lambda\_2 \times (z\_k1^\wedge m - z\_k2^\wedge m) \quad (24)$$

$$b_n = rand \times \left(\frac{[x_{n+1} + z_n]}{2} + rand \times \Delta z\right) \quad (25)$$

$$c_n = rand \times \left(\frac{[x_{n+1} + z_n]}{2} - rand \times \Delta z\right) \quad (26)$$

Based on the position the new solution is calculated from *equation (27)*. k_a and k_b are random number between 0 and 1.

$$z_n^{m+1} = k_a \times (k_b \times Z1_n^m + (1 - k_b) \times Z1_n^m) + (1 - k_a) \times Z3_n^m \quad (27)$$

$$Z3_n^m = Z_n^m - \lambda_1 \times (Z2_n^m - Z1_n^m) \quad (28)$$

4.2 Local Escaping Operator (LEO)

The LEO increases the efficiency of the algorithm. z_{LEO}^m is calculated from *equation (29)*

if rand<pr
if rand<0.5

$$Z_{LEO}^m = Z_n^{m+1} + g_1 \times (s_1 \times z_b - s_2 \times z_k^m) + g_2 \times \lambda_1 \times (s_3 \times (Z2_n^m - Z1_n^m) + s_3 \times (z_{k1}^m - z_{k2}^m))/2 \quad (29.1)$$

$$Z_n^{m+1} = Z_{LEO}^m \quad (29.2)$$

else

$$Z_{LEO}^m = z_b + g_1 \times (s_1 \times z_b - s_2 \times z_k^m) + g_2 \times \lambda_1 \times (s_3 \times (Z2_n^m - Z1_n^m) + s_3 \times (z_{k1}^m - z_{k2}^m))/2 \quad (29.3)$$

$$\mathrm{Z}_\mathrm{n}^{\mathrm{m}+1} = \mathrm{Z}_\mathrm{LEO}^\mathrm{m} \quad (29.4)$$

end

end

where g_1 is uniform random number between [-1,1], g_2 is random number from normal distribution with mean of 0 and standard deviation of 1, *pr* is probability. s_1, s_2 and s_3 are three random numbers as written below.

$$s_1 = H_1 \times 2 \times rand + (1 - H_1) \quad (30)$$

$$s_2 = H_1 \times rand + (1 - H_1) \quad (31)$$

$$s_3 = H_1 \times rand + (1 - H_1) \quad (32)$$

where H1 has value of 0 or 1.

To find the solution $\boldsymbol{z_k^m}$in *equation (33) and (34)* is used.

$$z_k^m = H_2 \times z_p^m + (1 - H_2) \times z_{rand} \quad (33)$$

$$z\_rand = Z\_min + rand(0,1) \times (Z\_max - Z\_min) \quad (34)$$

where zrand is new solution, z_p^m is randomly selected solution of the population and H2 is a binary value of 0 or 1. The Pseudo code of the GBO is shown in *table 1*.

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Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 3 | Pages 711-719 | e-ISSN: 2347-470X

Table 1: Pseudo code of GBO [18]

```
Initialize parameters pr, ε, and M
Find  initial population Z0 = [z01,z02,…,z0D]
Calculate f (Z0), n=1,….,N
Define zb and zw
      while (m<M)
        for n = 1 : N
            for i = 1 : D
                  Calculate z_n^{m+1} using (27)
            end
         if rand < pr
             Calculate ZLEO using (29)
             Zn = ZLEO
          end
        Update zb and zw
        end
     m=m+1
     end
return zb
```

5. METHODOLOGY TO SOLVE OPF USING GBO

In this work IEEE-69 bus system is modified to include wind turbines, fuel cell, solar photovoltaics, micro turbines and shunt compensator at bus numbers 14, 24, 31, 43 and 62 as reported in [13] and IEEE-69 bus data is taken from [13]. Parameters for renewable and non-renewable energy sources are mentioned in [13]. Modified IEEE-69 bus system is shown in *figure 1*. Methodology to solve OPF for distribution system is stepwise stated below.

Step 1: Load distribution network data of modified IEEE-69 bus system
Step 2: Declare the control variables and uncontrolled variables with lower and upper bound, Declare objective function and constraints
Step 3: Run GBO algorithm
Step 4: Run power Backward Forward Sweep power flow and calculate corresponding fitness value
Step 5: Repeat step 4 until set maximum iteration
Step 6: Return best solution

6. EXPERIMENT RESULTS AND NUMERICAL ANALYSIS

In this section OPF is solved using GBO and other state of art algorithms for modified IEEE-69 bus system. The performance of GBO is compared with other metaheuristic techniques such as Particle Swarm Optimization (PSO) [19], Ant Bee Colony (ABC) [20], Grey Wolf Optimization (GWO) [21] and JANA algorithm [13]. The comparison results and numerical analysis is reported in this section.

Experiment work is carried out in MATLAB 2021a and executed on Intel® Core i5 -7th generation CPU with 8GB RAM and windows 10 operating system.

6.1 Parameter Settings

Table 2 shows the algorithm specific parameter for GBO, PSO, ABC and GWO for performance comparison. All the algorithms are run with population size=30, dimension=5, maximum iteration = 100 and number of independent run = 30.

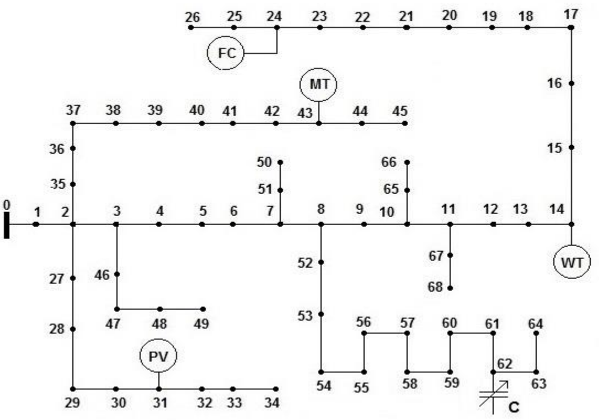

Figure 1: Modified IEEE-69 bus system [13]

Table 2: Parameter setting for algorithms

Algorithm	Parameter Setting
PSO	c1=2, c2=2, w1=0.9, w2=0.4
ABC	SN=50, MCN=100
GWO	a0=2
GBO	βmin=0.5, βmax=1.2, pr=0.5

6.2 Performance Comparison of GBO over other State of Art algorithms

Table 3 indicates statistical performance of GBO and other state of art algorithms on optimal power flow formulated in *section 2*. It shows that GBO has lowest mean value and lowest standard deviation compared to PSO, ABC, GWO, and JANA. The mean time of completion (TOC) is better than all the algorithms except GWO, but at the same time GWO is not converged to the minimum fitness value.

Table 3: Statistical results for OPF

Algorithm	Min	Mean	SD	Mean TOC (Sec.)
GBO	369.6746	369.6746	6.31E-06	201.7377
PSO	369.6746	369.6747	1.46E-04	203.5802
ABC	369.6756	369.7125	0.0502	447.9377
GWO	372.0941	407.6449	25.6433	95.9453
JANA	370.8761	373.8659	1.929	262.2558

In *table 4*, value of fuel cost (Fcost), power loss (Ploss) and voltage deviation (VD) for GBO and other state of art algorithm is reported. It can be observed that GBO has lowest value of fuel cost, power loss and voltage deviation compared other algorithms. *Figure 2* shows the convergence graph for said problem with GBO and other state of art algorithms is shown.

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Research Article | Volume 11, Issue 3 | Pages 711-719 | e-ISSN: 2347-470X

It can be clear observed that GBO converges fast due its local optima escaping behavior.

Table 4: Optimal value of fuel cost, power loss and voltage deviation

Algorithm	Fcost ($/hr)	Ploss (MW)	VD (pu)
GBO	86.32	0.12132	0.80094
PSO	86.33	0.12133	0.80095
ABC	86.32	0.12132	0.80095
GWO	87.43	0.12222	0.82665
JANA	86.61	0.12116	0.80233

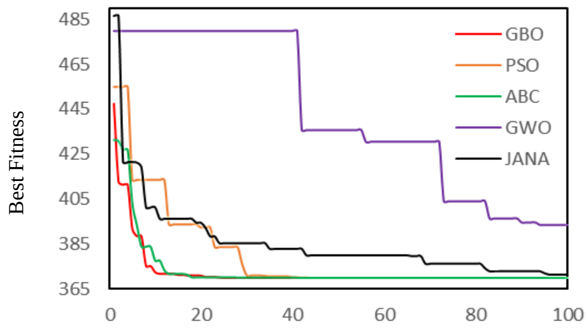

Figure 2: Convergence Graph

Table 5 indicates values of optimal control variable i.e. generator active power, generator bus voltages and shunt compensation for GBO and other state of art algorithms.

Table 5: Optimal control variable

Algorithm	Generator Active Power		Generator Voltages		Shunt VAR Compensation	
	Bus No	Pg (MW)	Bus No	Vg (pu)	Bus No	Qc (MVAR)
GBO	43	0	24	1.0025	62	1.2
	24	0.2392	0	1.0118	--	--
PSO	43	0	24	1.0025	62	1.2
	24	0.2392	0	1.0118	--	--
ABC	43	0	24	1.0025	62	1.2
	24	0.2408	0	1.0118	--	--
GWO	43	0.0072	24	1.0067	62	1.2
	24	0.3239	0	1.0118	--	--
JANA	43	0.0101	24	1.0036	62	1.1992
	24	0.3032	0	1.0109	--	--

For GBO, bus voltage and power under optimal control variable and branch power flow and loss is reported in Appendix I and Appendix II respectively.

7. CONCLUSION AND FUTURE WORK

Optimal power flow is classical problem of power system analysis. In this paper OPF is solved for distribution network having renewable energy sources like solar PV and wind turbine as DG. Apart from it to make distribution systems as real one, nonrenewable sources like fuel cell and micro turbines are also included as DG in system. It has been incorporated in modified IEEE-69 bus system to make model as real-world power system model.

Moreover, to solve OPF for distribution system, latest recently developed GBO technique is used. GBO takes 201.7377 sec with optimal value of 369.6746 with standard deviation of 3.61 E-06. Power system parameters values are also within safe limit. Performance of GBO proves the superiority over other state of art algorithms in terms of statistical analysis and convergence rate. According to No Free Lunch theorem, any optimization technique cannot solve all the real-world problem and there is always scope of modification in existing optimization algorithm.

Future work includes to test the behavior of GBO over other power system problems and to modify the GBO to increase convergence rate. Due to good performance of GBO, multi objective application of GBO can also be identified and solved using it for different engineering fields.

APPENDIX 1

Bus voltage and power under optimal control variable for GBO

Bus No	V (pu)	Angle (deg)	Pg (MW)	Qg (MVAr)	Qc (MVAr)	Pload (MW)	Qload (MW)
1	1.0118	-0.0011	0	0	0	0	0
2	1.0118	-0.0022	0	0	0	0	0
3	1.0117	-0.0056	0	0	0	0	0
4	1.0113	-0.0246	0	0	0	0	0
5	1.0057	-0.1133	0	0	0	0.0026	0.0022
6	0.9999	-0.2069	0	0	0	0.0404	0.03
7	0.9986	-0.23	0	0	0	0.075	0.054
8	0.9979	-0.2428	0	0	0	0.03	0.022
9	0.9964	-0.1941	0	0	0	0.028	0.019
10	0.9961	-0.1835	0	0	0	0.145	0.104

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11	0.9959	-0.1616	0	0	0	0.145	0.104
12	0.9973	-0.1586	0	0	0	0.008	0.005
13	0.9987	-0.1564	0	0	0	0.008	0.0055
14	1.0003	-0.1553	0.314	0.0916	0	0	0
15	1.0001	-0.1559	0	0	0	0.0455	0.03
16	1	-0.1591	0	0	0	0.06	0.035
17	1	-0.1591	0	0	0	0.06	0.035
18	1.0002	-0.1655	0	0	0	0	0
19	1.0003	-0.1696	0	0	0	1.00E-03	6.00E-04
20	1.0005	-0.1763	0	0	0	0.114	0.081
21	1.0005	-0.1768	0	0	0	0.005	0.0035
22	1.0007	-0.1824	0	0	0	0	0
23	1.0012	-0.1948	0	0	0	0.028	0.02
24	1.0025	-0.2244	0.2392	0.2006	0	0	0
25	1.0024	-0.2232	0	0	0	0.014	0.01
26	1.0024	-0.2229	0	0	0	0.014	0.01
27	1.0118	-0.0018	0	0	0	0.026	0.0186
28	1.0118	0.0053	0	0	0	0.026	0.0186
29	1.0123	0.0089	0	0	0	0	0
30	1.0123	0.0095	0	0	0	0	0
31	1.0127	0.0127	0.1899	0.0554	0	0	0
32	1.0125	0.0179	0	0	0	0.014	0.01
33	1.0123	0.0256	0	0	0	0.0095	0.014
34	1.0122	0.0267	0	0	0	0.006	0.004
35	1.0118	-0.0027	0	0	0	0.026	0.0186
36	1.0116	-0.009	0	0	0	0.026	0.0186
37	1.0114	-0.0114	0	0	0	0	0
38	1.0114	-0.012	0	0	0	0.024	0.017
39	1.0114	-0.0121	0	0	0	0.024	0.017
40	1.0107	-0.0228	0	0	0	0.0012	1.00E-03
41	1.0104	-0.0273	0	0	0	0	0
42	1.0104	-0.0279	0	0	0	0.006	0.0043
43	1.0104	-0.0281	0	0	0	0	0
44	1.0103	-0.0299	0	0	0	0.0392	0.0263
45	1.0103	-0.0299	0	0	0	0.0392	0.0263
46	1.0117	-0.0073	0	0	0	0	0
47	1.0105	-0.0511	0	0	0	0.079	0.0564
48	1.0067	-0.1869	0	0	0	0.3847	0.2745
49	1.0061	-0.2063	0	0	0	0.3847	0.2745
50	0.9985	-0.2297	0	0	0	0.0405	0.0283
51	0.9985	-0.2296	0	0	0	0.0036	0.0027
52	0.9959	-0.2965	0	0	0	0.0044	0.0035
53	0.9936	-0.3595	0	0	0	0.0264	0.019
54	0.9904	-0.4488	0	0	0	0.024	0.0172
55	0.9873	-0.5382	0	0	0	0	0
56	0.9699	-0.8761	0	0	0	0	0
57	0.9613	-1.0471	0	0	0	0	0

58	0.958	-1.1133	0	0	0	0.1	0.072
59	0.9541	-1.1974	0	0	0	0	0
60	0.949	-1.3739	0	0	0	1.244	0.888
61	0.9491	-1.4178	0	0	0	0.032	0.023
62	0.9493	-1.4835	0	0	1.2	0	0
63	0.9475	-1.467	0	0	0	0.227	0.162
64	0.9469	-1.462	0	0	0	0.059	0.042
65	0.996	-0.1824	0	0	0	0.018	0.013
66	0.996	-0.1824	0	0	0	0.018	0.013
67	0.9956	-0.1558	0	0	0	0.028	0.02
68	0.9956	-0.1558	0	0	0	0.028	0.02
0	1.0118	0	3.1701	1.203	0	0	0

Appendix II

Branch power flow and loss under optimal control variable for GBO

From Bus	To Bus	P (MW)	Q (MVAr)	Ploss (MW)	Qloss (MVAr)
0	1	3.1701	1.2029	3.50E-05	8.41E-05
1	2	3.17	1.2028	3.50E-05	8.41E-05
2	3	3.0924	1.0636	9.78E-05	2.35E-04
3	4	2.2409	0.4516	8.00E-04	9.37E-04
4	5	2.2293	0.4457	0.0117	0.0059
5	6	2.2145	0.4373	0.0121	0.0062
6	7	2.1713	0.4059	0.0028	0.0014
7	8	2.0509	0.3202	0.0013	6.78E-04
8	9	0.2159	0.237	5.29E-04	1.75E-04
9	10	0.1878	0.2179	9.75E-05	3.22E-05
10	11	0.0068	0.0879	3.48E-05	1.15E-05
11	12	-0.1945	-0.0562	2.65E-04	8.74E-05
12	13	-0.2028	-0.0613	2.93E-04	9.68E-05
13	14	-0.2111	-0.0669	3.24E-04	1.07E-04
14	15	0.1029	0.0247	1.37E-05	4.54E-06
15	16	0.0574	-0.0053	7.76E-06	2.57E-06
16	17	-0.0026	-0.0403	4.78E-08	1.63E-08
17	18	-0.0626	-0.0753	1.96E-05	6.48E-06
18	19	-0.0626	-0.0753	1.26E-05	4.13E-06
19	20	-0.0636	-0.0759	2.09E-05	6.91E-06
20	21	-0.1777	-0.1569	4.90E-06	1.61E-06
21	22	-0.1827	-0.1604	5.86E-05	1.94E-05
22	23	-0.1828	-0.1605	1.28E-04	4.22E-05
23	24	-0.2112	-0.1806	3.59E-04	1.19E-04
24	25	0.028	0.02	2.27E-06	7.51E-07
25	26	0.014	0.01	3.18E-07	1.05E-07
2	27	-0.1083	0.0099	3.17E-07	7.78E-07
27	28	-0.1343	-0.0087	7.06E-06	1.73E-05
28	29	-0.1603	-0.0274	6.41E-05	2.12E-05
29	30	-0.1603	-0.0274	1.13E-05	3.74E-06
30	31	-0.1604	-0.0274	5.65E-05	1.87E-05

31	32	0.0295	0.028	8.45E-06	2.84E-06
32	33	0.0155	0.018	5.87E-06	1.94E-06
33	34	0.006	0.004	4.67E-07	1.54E-07
2	35	0.1858	0.1292	1.37E-06	3.37E-06
35	36	0.1597	0.1106	1.47E-05	3.60E-05
36	37	0.1337	0.092	1.69E-05	1.98E-05
37	38	0.1337	0.092	4.88E-06	5.70E-06
38	39	0.1097	0.075	1.94E-07	2.26E-07
39	40	0.0857	0.0579	4.76E-05	5.56E-05
40	41	0.0844	0.0569	1.96E-05	2.30E-05
41	42	0.0844	0.0569	2.60E-06	3.03E-06
42	43	0.0784	0.0526	5.02E-07	6.32E-07
43	44	0.0784	0.0526	5.94E-06	7.49E-06
44	45	0.0392	0.0263	1.23E-08	1.64E-08
3	46	0.8507	0.611	2.27E-05	5.62E-05
46	47	0.8501	0.6096	5.69E-04	0.0014
47	48	0.7695	0.5493	0.0016	0.0039
48	49	0.3847	0.2745	1.13E-04	2.77E-04
7	50	0.0441	0.031	1.69E-06	8.60E-07
50	51	0.0036	0.0027	4.21E-08	1.41E-08
8	52	1.8009	0.0592	0.0036	0.0018
52	53	1.7924	0.0536	0.0041	0.0021
53	54	1.7604	0.0318	0.0056	0.0029
54	55	1.731	0.0118	0.0054	0.0027
55	56	1.7005	0.0016	0.0305	0.0102
56	57	1.6855	-0.0034	0.015	0.005
57	58	1.6796	-0.0054	0.0058	0.0019
58	59	1.5731	-0.0794	0.0066	0.002
59	60	1.5644	-0.0838	0.0086	0.0044
60	61	0.3197	-0.9721	7.07E-04	3.60E-04
61	62	0.2866	-0.9957	0.0011	5.49E-04
62	63	0.286	0.204	6.10E-04	3.10E-04
63	64	0.059	0.042	3.80E-05	1.94E-05
10	65	0.036	0.026	2.50E-06	7.58E-07

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