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Multi-objective optimization of distributed generation with voltage step constraint

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Abstract

This paper presents the multi-objective optimization for high penetration of different type of distributed generations (DGs) considering voltage step constraint. In most of the studies in literature, the commonly used constraints are bus voltage limits and line power capacity limit. In this paper, it is analyzed that voltage step constraint affects the location, size and power factor of DG in distribution network. The studies are carried out for 17-bus, 38-bus and 76-bus distribution systems.

***Keywords*:** Distributed generation, distribution system, distributed generation planning, genetic algorithm.

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1. Introduction

The limitation of traditional power generation, increasing power demand and benefits of distributed generation (DG) have been renewed the interest in DG and increased the DG penetration into distribution systems (Ackermann *et al*, 2001; Chiradejaand *et al*, 2004; El-Khattam *et al*, 2004; Pepermans *et al*, 2005; Driesen *et al*, 2006). The DG could accrue the benefits only when DGs are placed at optimum location with optimum size. For proper DG placement, the optimization techniques are employed in such a way that system operating constraint should not be violated and system should operate economically. The single-objective and multi-objective functions, which could be optimized using genetic algorithm (GA), are used for proper allocation of DG.

The multi-objective performance index based approach using GA for optimal DG allocation has been presented by many researchers with different compositions of indices, but voltage step constraints have been considered by few researchers for optimal DG planning. (Celli *et al*, 2005), proposed a GA based multi-objective formulation for the siting and sizing of DG in distribution system. This methodology allows the planner to achieve the best compromised solution considering cost of system upgrading, cost of real power loss, cost of energy which is not supplied, and cost of energy required by the customers. (Ochoa *et al*, 2006) present a multi-objective performance index for distribution systems DG which considers a wide range of technical problems. The technical impact on medium-voltage level reliability as well as electrical power quality is assessed and used distribution system impact indices. (Ochoa *et al*, 2008), present a multi-objective performance index for distribution systems with time-varying distributed generation and load, considering a number of issues such as losses, voltages, reserve capacity of conductors, and short circuit current. (Singh *et al*, 2009) present a multi-objective performance index for optimal size and location of DG in distribution systems for different voltage dependent load models and concluded that voltage dependent load models significantly affect the optimal location and size of DG.

The voltage-step constraint is one of the inevitable constraints for appropriate size and location of DG. This constraint has been implemented by the authors for distributed generation capacity analysis (Dent *et al*, 2010). From the literature review (Payasi *et al*, 2011), it is found that the researchers have not considered voltage step constraint (VSL) in multi-objective optimization problem.

In this paper, multi-objective function is formed for optimum location and size of different type of DGs to maximize the DG size for high penetration. It is shown that voltage step constraint can significantly affect the size and location of DG in distribution network. To keep the problem focused on study of impact of voltage step constraint on size and location of single DG, the cases of single DG placement are presented. However, a generalized method is proposed which can be applied for multiple DG by increasing the number of variables in GA method.

This paper is structured as follows: Section 2 presents the voltage step issue. Section 3 defines the impact indices. Section 4 presents the multi-objective function and GA based methodology. The result and discussions are presented in section 5. The conclusions drawn from the study are presented in section 6.

2. Voltage Rise and Voltage step

The voltage rise and voltage step are explained considering two bus system (Figure 1) consists of a grid supply point (GSP) at bus *A*, load ($P_{D\,B}+jQ_{D\,B}$) and DG (capable of supplying both real power and reactive power ($P_{DG\,B}$ + $Q_{DG\,B}$) at bus *B*. The some amount of the load is met by DG, and hence the power drawn from the grid through line ($R+jX$) is reduced. Thus DG results steady state voltage rise between buses *A* and *B* ($V_{rise\,B}$) is expressed approximately as follows (Dent *et al*, 2010).

$$V_{rise\,B} = (P_{DG\,B} - P_{D\,B})R + (Q_{DG\,B} - Q_{D\,B})X \tag{1}$$

On subtracting the voltage at B without DG ($V_{WODG\,B}$) from the voltage at B with DG ($V_{WDG\,B}$), gives the voltage step at bus B ($V_{step\,B}$) on loss of the DG (assuming that the voltage at A remains constant, i.e., 1.00 p.u.) which is expressed as follows:

$$V_{step\,B} = V_{WDG\,B} - V_{WODG\,B} = -(P_{DG\,B}\,R + Q_{DG\,B}\,X) \tag{2}$$

If DG is capable of supplying only active power, then (2) is modified as:

$$V_{step\,B} = V_{WDG\,B} - V_{WODG\,B} = -P_{DG\,B}\,R \tag{3}$$

In this paper, the bus-1, i.e., grid supply point (*GSP*) of test system is taken as slack bus for power flow study. For every size of DG, the voltage step in per unit (V_{step}) is calculated at every bus as follows:

$$V_{step\,i} = \left(V_{WDG\,i} - V_{WODG\,i}\right)/V_{WDG\,i}\,, \quad for\ i = 2\ to\ N_B \tag{4}$$

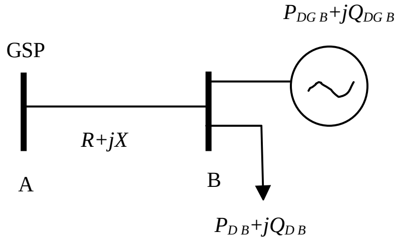

Figure 1. Two-bus system

3. Impact Indices

The five numbers of indices have been considered in multi-objective performance index (*MOPI*) formulation. These are defined as follows:

3.1 Real power loss index (PLI): The lesser value of this index indicates lower real power loss. This index is expressed as follows:

$$PLI = \frac{P_{LWDG}}{\left|Q_{LWODG}\right|} \times 100 \tag{5}$$

3.2 Reactive power loss index (QLI): The lesser value of this index indicates lower reactive power loss. This index is expressed as follows:

$$QLI = \frac{Q_{LWDG}}{Q_{LWODG}} \times 100 \tag{6}$$

3.3 Voltage profile index (VPI): It is related to maximum voltage drop between root bus and each bus. Lower value of this index indicates improvement in voltage profile. This index is expressed as follows:

$$VPI = \max\left(\frac{|V_1| - |V_i|}{|V_1|}\right)\times 100, \quad for\ i = 2\ to\ N_B \tag{7}$$

3.4 Line capacity index (LCI): Lower value of this indicates availability of more line capacity. It is expressed as follows:

$$LCI = \max\left(\frac{|S_{ij}|}{|CS_{ij}|}\right)\times 100,\ for\ ij = 1\ to\ N_L \tag{8}$$

3.5 Apparent power intake (S_{intake}) index (*SII*): The lower value of this index indicates lesser S_{intake} and more availability of substation capacity. This index is expressed as follows:

$$SII = \frac{|S_{intakeWDG}|}{|S_{intakeWODG}|}\times 100 \tag{9}$$

4. **Methodology**

4.1 Multi-objective formulation

Multi-objective index, to assess the performance of the network with DG, takes into account the combination of different indices by strategically assigning the weighting factor to each index for optimal DG size, power factor, and location planning with voltage step constraint including usual constraint, i.e., bus voltage limits and line capacity limit. The multi-objective performance index (MOPI) may be formulated with normalized weights of indices emphasizing loss reduction for economical operation, or emphasizing deferment of substation upgrade. The MOPI, considering PLI, QLI, VPI, LCI, and SII, is formulated as follows.

$$MOPI = w_1.PLI + w_2.QLI + w_3.VPI + w_4.LCI + w_5.SII \tag{10}$$

where, $\sum_{n=1}^{5} w_n = 1.0\ \Lambda\ w_n \in [0,1]$

The weighting factors used for high penetration, to defer the substation upgrade, of DG are considered as follows:

w_1=0.1, w_2 =0.1, w_3 =0.15, w_4 =0.20, w_5 = 0.45

The above objective is minimized subject to the following inequality constraints:

$$V_{\min} \le |V_i| \le V_{\max}, \quad for\ i = 1 to\ N_B \tag{11}$$

$$S_{ij} \le CS_{ij}^{\max}, \quad for\ i, j \in N_L \tag{12}$$

$$V_{step\,i} \le V_{step}^{\max}, \quad for\ i = 1\ to\ N_B \tag{13}$$

$$P_{DG} < P_{\text{intake}} \tag{14}$$

In this paper, voltage limits and *VSL* are taken as follows:

$V_{\min} = 0.95$ p.u., $V_{\max} = 1.03$ p.u., and $V_{step}^{\max} = 3\%$

4.2 Type of distributed generation

The classification of traditional and non-traditional DGs from different points of view, i.e., constructional, technological, size, and power-time duration, have been described in (El-Khattam *et al*, 2004). However, DGs may be grouped into four major types on the basis of their terminal characteristics in terms of real and reactive power delivering capability (Hung *et al,* 2010; Payasi *et al*, 2012):

Type 1: This type of DG is capable of delivering only active power. The photovoltaic, micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters, are the example of this type. However, according to current situation and grid codes these may consume or produce reactive power

Type 2: This type of DG is capable of delivering both active and reactive power. The DG unit based on synchronous machine, i.e., cogeneration, gas turbine, etc., comes under this type.

Type 3: This type of DG is capable of delivering only reactive power. The synchronous compensators such as gas turbines are the example of this type.

Type 4: This type of DG is capable of delivering active power but consuming reactive power. The induction generators, which are used in wind farms, mainly come under this category. However, doubly fed induction generator (DFIG) systems may consume or produce reactive power i.e. operates similar to synchronous generator.

4.3 Test cases

The following test cases are considered for optimal size and location of DGs, assuming with constant power load, for minimization of *MOPI* in 17-, 38- and 76-bus systems.

- Type 1 DG with and without VSL constraint.
- Type 2 DG with and without VSL constraint.
- Type 3 DG with and without VSL constraint.
- Type 4 DG with and without VSL constraint.

4.4 System

A 38-bus distribution system (Singh *et al*, 2009) is adopted as base system, network is shown in Figure 2 in Appendix. The line impedances, load data and the line capacity limits, shown in Table 5, are expressed in p.u. at the base voltage of 12.66 kV and base MVA of 1.0 MVA (Singh *et al*, 2009; Baran *et al*, 1989). The test systems of 17- bus and 76-bus are derived from 38-bus system.

4.5 GA implementation

GA based optimization technique has been considered in DG planning by authors in (Goldberg, 1989; Celli *et al*, 2001; Bakirtzis *et al*, 2002; Chakraborty, 2005; Singh *et al*, 2008) to optimize the multi-objective performance index (*MOPI*).

The evaluation of the objective function depends only on location, size (P_{DG}), and power factor (PF_{DG}) of DG if the network configuration remains same. Because of above reason each solution is checked for proper location of DG ranging from 2 to N_B, size of DG limited to P_{intake}, and power factor of DG limited between 0.8 ld to 0.8 lg.

The GA starts with random generation of initial population of the possible solutions. For each solution the size of DG, power factor of DG, and a location of DG, DG-bus, are generated within system constraints. The numbers of size-power_factor-location sets are randomly selected, multi-objective function is evaluated, and system constraints are verified. The solution is accepted, if any constraint is not violated, else solution is rejected.

Once initial population is constituted, the genetic operators are applied for set number of times to produce new solutions. The crossover (swept with probability of 0.5) and mutation (with probability of 0.05) operators are applied. If any of the system constraints is violated, the new solution is not accepted.

Finally, according to steady-state topology of GA, the new population is constituted comparing old and new solutions and selecting the best among them. The algorithm stops when the maximum number of generations is reached or difference between objective function value of the best and worst individual becomes smaller than specified. The computational algorithm is as follows:

Step 1: Read the load data, line data, number of buses, voltage limits, voltage step change *limit (VSL=3%), power factor (*pf) limits (0.8 l*g* to 0.8 l*d*), maximum number of iterations (mi=50), maximum number of runs (mr=10), and weights.
Step 2: Take one of the DG types
Step 3: Run power flow program without DG and save the required quantities corresponding to WODG.
Step 4: Randomly generate size-pf-location of DG in a predefined range of DG sizes, buses, i.e., 2 to N_B, and power factor and Set k=1.
Step 5: if kr>mr go to 16
Step 6: if k>mi, go to 14
Step 7: Run power flow programme and calculate real power loss of system for each of the size-pf-location sets and record the power loss and its corresponding size-pf-location.
Step 8: Check the voltage limits, VSL at all the buses, and line capacity limit for all the lines for each of the size-pf-location sets.
Step 9: Accept the sets for next generation of population for which NVLVB=NLCLVL =0 (and NVSLVB =0 when VSL constraint is considered). If population is zero go to step 4
Step10: Obtain the size-pf-location(k) set for minimum value of multi-objective performance index ((MOPI (k)).
Step11: Use the available population of size-pf-location set (parent population) for cross over and mutation for obtaining new generation (offspring) of population.
Step12: Use the newly generated population size i.e. offspring and parents as new generation.
Step13: k = k+1 and go to step 6
Step14: size-pf-location(kr) = size-pf-location(k) and MOPI (kr) = MOPI (k).
Step15: kr = kr+1 go to 5
Step16: The size, pf, and location corresponding to minimum loss out of number of runs are the optimum size-pf-location pair. For optimum size, pf, and location run the power flow and obtain all the relevant quantities such as P_{DG}, Q_{DG}, P_L , Q_L, S_{intake}, P_{intake}, Q_{intake}, S_{sys}, PLI, QLI, VPI, LCI.
Step 17: go to step 2 till all DG types are selected.
Step 18: stop

5. Simulation Result and Discussion

The multi-objective optimization performance index consists of five indices including S_{intake}. The weight given to S_{intake} is more compared to others for high penetration of DG. The DG size and location along with other relevant quantities obtained for different type of DGs in 17-, 38-, and 76-bus distribution systems are given in Table 2, Table 3, and Table 4 respectively.

5.1 Effect of DG-type on NVSLVB

It is observed from Table 1 that the *NVSLVB* is 25 for T1 and T4 in case of 38-bus system, whereas, no violation of voltage step limit for any type of DG in case of 17- and 76-bus systems. It is because of load condition, i.e., different system have different loads

Table 1. *NVSLVB* without VSL constraint for different type of DGs

Type of dgs	*NVSLVB* for minimum P_L		
	17-bus	38-bus	76-BUS
T1	0	25	0
T2	0	0	0
T3	0	0	0
T4	0	25	0

5.2 DG size

In case of 16- and 76-bus systems, the size of each type of DG remains same when *VSL* constraint is considered, whereas, in case of 38-bus system, the size of DG is affected for T1 and T4 when VSL constraint is considered.

5.3 DG location

In case of 16- and 76-bus systems the optimum location of each type of DG remains same when VSL constraint is considered, whereas, in case of 38 bus system, the optimum location of DG is affected for T1 and T4 when VSL constraint is considered. The optimum location for each type of DG is 7 and 2 in 16-bus and 76-bus systems respectively, whereas, in case of 38-bus system the optimum locations are different for different type of DGs. Further, the P_{DG} is more when VSL is considered for T1 and T2 in case of 38-bus system. It is because of shifting of optimal location towards the root bus, i.e., substation bus.

5.4 Real and reactive power losses

It is observed that in all three test systems the P_L and Q_L are lesser for T2 compared to T1, T3, and T4. The reason is that T2 is capable of supplying real and reactive power both and voltage is improved. The improvement of voltage lowers the current flow and hence power losses are lesser for T2 compared to other type of DGs

5.5 MVA intake (S_{intake})

It is observed that in all three test systems the MVA intake is lesser for T2 compared to T1, T3, and T4. The reason is that T2 is capable of supplying real and reactive power both. The penetration of T2 reduces the real and reactive power intake from substation and hence MVE intake is lesser for T2 compared to other type of DGs.

Table 2. Value of relevant quantities corresponding to minimum MOPI for 17-bus system

DG Type	W/WO DG	W/WO VSL	P_{DG} (p.u.)	Q_{DG} (p.u.)	DG bus	DG_pf	S_{intake} (p.u.)	P_L (p.u.)	Q_L (p.u.)
	WODG	-	-	-			1.5994	0.0161	0.0140
T1	WDG	WOVSL	0.7989	-	7	1.0	0.9393	0.0054	0.0043
		WVSL	0.7989	-		1.0	0.9393	0.0054	0.0043
T2	WDG	WOVSL	0.7281	0.3731	7	0.89	0.8263	0.0032	0.0023
		WVSL	0.7281	0.3731	7	0.89	0.8263	0.0032	0.0023
T3	WDG	WOVSL	0.0	0.48	7	0.0	1.4473	0.0136	0.0118
		WVSL	0.0	0.48	7	0.0	1.4473	0.0136	0.0118
T4	WDG	WOVSL	0.7909	-0.1127	7	0.99lg	1.033	0.0071	0.0058
		WVSL	0.7909	-0.1127	7	0.99lg	1.033	0.0071	0.0058

Table 3. Value of relevant quantities corresponding to minimum MOPI for 38-bus system

DG Type	W/WO DG	W/WO VSL	P_{DG} (p.u.)	Q_{DG} (p.u.)	DG bus	DG_pf	S_{intake} (p.u.)	P_L (p.u.)	Q_L (p.u.)
	WODG	-	-	-			4.5963	0.1889	0.1260
T1	*WDG*	*WOVSL*	3.3203	0.0	6	1.0	2.4274	0.1046	0.0755
		WVSL	3.8145	0.0	4	1.0	2.3967	0.1336	0.0964
T2	*WDG*	*WOVSL*	3.4753	2.1538	3	0.85ld	0.4355	0.1247	0.0922
		WVSL	3.4753	2.1538	3	0.85ld	0.4355	0.1247	0.0922
T3	*WDG*	*WOVSL*	0.0	2.2734	6	0.0	3.8646	0.1475	0.1006
		WVSL	0.0	2.2734	6	0.0	3.8646	0.1475	0.1006
T4	*WDG*	*WOVSL*	3.2559	-0.4639	6	0.99lg	2.9135	0.1275	0.0899
		WVSL	3.3716	-0.4804	7	0.99lg	2.9131	0.1386	0.0988

Table 4. Value of quantities corresponding to minimum MOPI for 76-bus system

DG Type	W/WO DG	W/WO VSL	P_{DG} (p.u.)	Q_{DG} (p.u.)	DG bus	DG_pf	S_{intake} (p.u.)	P_L (p.u.)	Q_L (p.u.)
	WODG	-	-	-			9.8504	0.3419	0.2484
T1	WDG	WOVSL	8.2721	0.0	2	1.0	5.3275	0.3019	0.2484
		WVSL	8.2721	0.0	2	1.0	5.3275	0.3019	0.2484
T2	WDG	WOVSL	9.2137	5.3055	2	0.84ld	0.0133	0.2856	0.2188
		WVSL	9.2137	5.3055	2	0.84ld	0.0133	0.2856	0.2188
T3	WDG	WOVSL	0.0	3.7535	2	0.0	8.3759	0.2975	0.2232
		WVSL	0.0	3.7535	2	0.0	8.3759	0.2975	0.2232
T4	WDG	WOVSL	7.3984	-1.0542	2	0.99lg	6.4407	0..3094	0.2314
		WVSL	7.3984	-1.0542	2	0.99lg	6.4407	0..3094	0.2314

6. Conclusions

The multi-objective optimization is implemented for high penetration of different type of DGs in 17-, 38- and 76-bus systems considering voltage step constraint including voltage and line capacity constraints.

- The investigations show that number of voltage step limit violated buses is zero for each type of DG in case of 17- and 76-bus systems, whereas, it is zero only for T2 and T3 in case of 38-bus system.
- The MVA intake is lesser for T2 compared to other type of DG in 16-, 38- and 76-bus systems.
- The real and reactive power losses are lesser for T2 compared to other type of DG in 16-, 38- and 76-bus systems.
- The optimum location of different type of DGs is same in 17- and 76-bus system, whereas it is different for different type of DGs in 38-bus system when *VSL* constraint is considered.

Nomenclature

$CS_{i,j}$	MVA capacity of line *i-j* (p.u.).
ld, *lg*	Leading, lagging
MOPI	Multi-objective performance index.
NLCLVL	Number of line capacity limit violated lines.
NVLVB	Number of voltage limit violated buses.
NVSLVB	Number of voltage step limit violated buses.
P_D , Q_D	Total system real and reactive power demand (p.u.).
P_{DG}, Q_{DG}, S_{DG}	Real, reactive, and MVA power of DG (p.u.).
P_i , Q_i	Real and reactive power injection at bus i (p.u.).
P_{intake} , Q_{intake}	Real and reactive power intake at main substation (p.u.).

P_L , Q_L	System real and reactive power loss (p.u.).
$S_{i,j}$	MVA Power flows in line *i-j* (p.u.).
S_{intake}	Apparent power (MVA) intake at bus-1 (p.u.).
T1,T2,T3,T4	Type1 DG, Type2 DG, Type3 DG, Type4 DG
V_i	Voltage of i^{th} bus (p.u.).
$V_{step\ i}$, *VSL*	Voltage step at i^{th} bus (p.u.), Voltage step limit (%).
WDG, *WODG*	With and without DG.
N_B , N_L	Number of buses and number of lines.

Appendix

Table 5. Lines parameter and load data for 38-bus system [9]

F	T	Line impedance (p. u.)		L	S_L (p.u.)	Load on to bus (p. u.)	
		R	*X*			*P*	*Q*
1	2	0.000574	0.000293	1	4.60	0.10	0.06
2	3	0.003070	0.001564	6	4.10	0.09	0.04
3	4	0.002279	0.001161	11	2.90	0.12	0.08
4	5	0.002373	0.001209	12	2.90	0.06	0.03
5	6	0.005100	0.004402	13	2.90	0.06	0.02
6	7	0.001166	0.003853	22	1.50	0.20	0.10
7	8	0.004430	0.001464	23	1.05	0.20	0.10
8	9	0.006413	0.004608	25	1.05	0.06	0.02
9	10	0.006501	0.004608	27	1.05	0.06	0.02
10	11	0.001224	0.000405	28	1.05	0.045	0.03
11	12	0.002331	0.000771	29	1.05	0.06	0.035
12	13	0. 009141	0.007192	31	0.50	0.06	0.035
13	14	0.003372	0.004439	32	0.45	0.12	0.08
14	15	0.003680	0.003275	33	0.30	0.06	0.01
15	16	0.004647	0.003394	34	0.25	0.06	0.02
16	17	0.008026	0.010716	35	0.25	0.06	0.02
17	18	0.004538	0.003574	36	0.10	0.09	0.04
2	19	0.001021	0.000974	2	0.50	0.09	0.04
19	20	0.009366	0.008440	3	0.50	0.09	0.04
20	21	0.002550	0.002979	4	0.21	0.09	0.04
21	22	0.004414	0.005836	5	0.11	0.09	0.04
3	23	0.002809	0.001920	7	1.05	0.09	0.05
23	24	0.005592	0.004415	8	1.05	0.42	0.20
24	25	0.005579	0.004366	9	0.50	0.42	0.20
6	26	0.001264	0.000644	14	1.50	0.06	0.025
26	27	0.001770	0.000901	15	1.50	0.06	0.025
27	28	0.006594	0.005814	16	1.50	0.06	0.02
28	29	0.005007	0.004362	17	1.50	0.12	0.07
29	30	0.003160	0.001610	18	1.50	0.20	0.60
30	31	0.006067	0.005996	19	0.50	0.15	0.07
31	32	0.001933	0.002253	20	0.50	0.21	0.10
32	33	0.002123	0.003301	21	0.10	0.06	0.04
8	34	0.012453	0.012453	24	0.50	0.00	0.00
9	35	0.012453	0.012453	26	0.50	0.00	0.00
12	36	0.012453	0.012453	30	0.50	0.00	0.00
18	37	0..003113	0.003113	37	0.50	0.00	0.00
25	38	0.003113	0.002513	10	0.10	0.00	0.00

F = From bus, T = To bus, L = line number, S_L = Line apparent power limit., *P* = Real power load , *Q*= Reactive power load

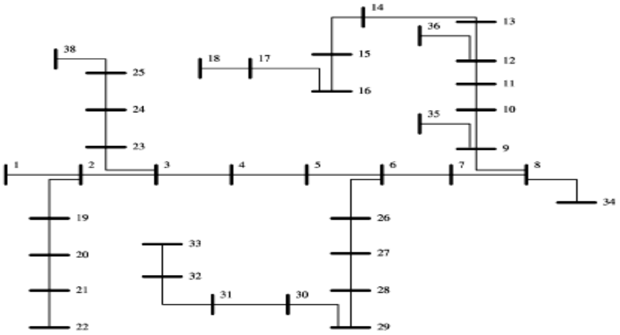

Figure 2. The 38-bus test system [9]

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