Role Analysis of *Distributed Generation* Towards *Transmission Expansion Planning* Using MILP

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***Abstract*— Electricity demand increase as function of population and economic activity growth. To meet the demand growth, one kind of approaches to expand electrical system is to calculate the need of generating unit and the result will be used to determine the needs of transmission line. In this research, a model was developed with focused on transmission line expansion based on Mix Integer Linear Programming method. The objective function was to minimize overall investment cost for transmission and operating cost of all generating units. The developed model was implemented in 6-bus Garver's test system. Distributed generation implementation impact is also studied in this study in term of network configuration and overall expansion cost. The results show that distributed generation implementation will differ the network configuration and reduce the overall system cost, with overall system cost with and without distributed generation implementation was $106.4 million and $103.18 million respectively.**

***Keywords*— Transmission Line Expansion, Distributed Generation, Network Configuration, Mix Integer Linear Programming.**

NOMENCLATURE

Index	
dg	candidate distributed generation unit
d	load
g	installed power plant unit
l	transmission line
n	bus
o	operating conditions
Assemblage	
$r(l)$	receiver bus on *l* transmission line
$s\ (l)$	receiver bus on *l* transmission line
Ω_n^C	candidate distributed generation unit located in *n* bus
Ω_n^D	load located in *n* bus
Ω_n^E	the existing power plan in *n* bus
Parameters:	
B_l	*l* transmission line susceptibility value
C_{dg}^C	*c* candidate distributed generation unit production cost ($/MWh)
C_g^E	production cost of installed *g* power plant ($/MWh)
C_d^{LS}	load shedding costs at *d* load ($ / MWh)
F_l^{max}	transmission line capacity (MW)
I_{dg}^C	*c* candidate distributed generation unit investment cost ($/MW)
$\tilde{I}_{dg}^C$	*c* candidate distributed generation unit annual investment cost ($/MW)
$P_{dg}^{C\,max}$	minimum production capacity of *c* candidate power plant unit (MW)
P_{dgq}^{Option}	option *q* production capacity from candidate power plant unit c (MW)
$P_d^{D\,max}$	*d* load capacity [MW]
$P_g^{E\ max}$	production capacity of installed *g* power plant (MW)
$\tilde{I}_l^L$	*l* transmission line candidate investment costs [$/MW]
$\tilde{I}^{L,max}$	annual budget for *l* line candidate development [$]
Binary Variable	
x_l^L	binary variable is valued as 1 if transmission line candidate is built and it is valued as 0 for the opposite situation
Continuous Variable	
p_c^C	power generated by *c* (MW) candidate power plant unit
$p_c^{C\,max}$	capacity of *c* (MW) candidate power plant unit
p_g^E	power generated by installed *g* (MW) power plant unit
p_l^L	power flow through transmission line
p_g^G	power generated by the *g* [MW] power plant unit
p_l^L	flowing power through *l* [MW] transmission line
p_d^{LS}	load shedding by *d* [MW] load
θ_n	voltage angle on *n* [rad] bus

I. INTRODUCTION

The growth in demand for electricity is always positive, it is driven by two dominant factors, i.e. population growth and economic activity growth. Electric power system planning and development such as transmission line capacity are administered to meet the electrical energy demand. Calculation result in this planning should be on an optimal value and that value must be on the allowed tolerance limit. For a too high optimal value, the planning would result in too

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high investment cost. On the other hand, if optimal planning result is too low, the activity supported by the electric energy would be disrupted. It is a quite difficult challenge faced by the electricity provider.

Basically, the power system planning consists of power plant capacity planning which is known as Generation Expansion Planning (GEP) and transmission network planning known as Transmission Expansion Planning (TEP). A very common method used in GEP calculation is optimization method to obtain electricity generation with lowest cost. Mixed integer linear programming (MILP) is a frequently used model in GEP, such as in integrated capacity generator development to obtain minimum investment and operation costs by showing the ENS (energy not served) reliability index and its impact on the environment [1]. MILP can also be applied in the power plant capacity development by including uncertainty variables through two-stage optimization, uncertainty of water resources as a primary energy as well as load and wind potential energy uncertainties to meet greenhouse emissions target [2].

In recent years, the construction of power plants with renewable natural resources by implementing distributed generation (DG) is rapidly increasing. Therefore, transmission network addition planning should incorporate features from renewable natural resources [3]. The addition of transmission capacity is fundamental for a safe and efficient power system operation in the long run. Today, the transmission capacity addition paradigm has changed for the high penetration from renewable natural resources which certainly affect the planning costs. This generation source provides several distinctive features such as natural resources diversity and availability, its distance length from load centre, and planning possibility which can affect both short-term or long-term plans. Therefore, the transmission capacity addition planning must combine economic and technical impacts associated with renewable natural resources generator in order to determine the right economic value in the long turn. With the renewable natural resources penetration, the transmission capacity addition planning costs will change. It probably adds or reduces the transmission capacity addition planning costs. It can be seen through the TEP modelling which combines features from renewable natural resources types. Then, MILP method is used to do a calculation optimization for the modelling. MILP itself is a method widely used in TEP calculation with a pretty accurate result.

II. THEORETICAL FRAMEWORK

A. Distributed Generation

DG technology can be divided into two types based on its energy source, renewable and non-renewable. Renewable technologies include solar, light or thermal, wind, geothermal and oceanic energy. Non-renewable technologies include engine internal combustion, ice, combined cycle, combustion turbine, micro turbine, and fuel cell. Most of DG energy sources are designed using green energy which is assumed to be pollution free [4].

In previous years, DG installations showed an increase in the growth number in distribution networks throughout the world due to increased promotion of renewable energy sources utilization and the assisted generation systems development. As we know DG gives an effect on the power flow of the system associated with distribution network, power loses on that network will also be affected [5].

B. TEP Model

The developed TEP model is MILP through a deterministic-static approach. The model has objective functions in (1) with constraint functions in (2) to (12). This MILP model has optimization variables in the set $\Delta = \{x_l^L, p_{go}^G, p_{do}^{LS}, p_{lo}^L, p_{do}^D, \theta_{no}\}$.

$$\min \sum_{o=1}^{no} \rho \left[\sum_{g=1}^{ng} C_g^E p_{go}^E + \sum_{d=1}^{nd} C_d^{LS} p_{do}^{LS} \right] + \sum_{l \in \Omega^{L+}} \tilde{I}_l^L x_l^L \, . \tag{1}$$

There are two limitation groups, i.e. investment limitations and operation. Investment limits are used to determine the capacity needed by the transmission line candidates. Investment limitations from the model is stated in equation (2) to (3).

$$\sum_{l \in \Omega^{L+}} \tilde{I}_l^L x_l^L \leq \tilde{I}_l^{L,max} \tag{2}$$

$$x_l^L = \{0,1\} \qquad \forall l \in \Omega^{L+} \, . \tag{3}$$

Limit (2) states that addition from transmission line shall not exceed the total budget provided for the transmission line addition. Limit (3) shows that transmission line to be built is determined by x_l^L binary variable. Operation limits of TEP model is stated in (4) to (12).

$$\sum_{g \in \Omega_n^E} p_{go}^E - \sum_{l|s(l)=n} p_{lo}^L + \sum_{l|r(l)=n} p_{lo}^L = \sum_{d \in \Omega_n^D} \left(p_{do}^{D^{maks}} - p_{do}^{LS} \right) \quad \forall n \tag{4}$$

$$p_{lo}^L = B_l \left(\theta_{s(l)o} - \theta_{r(l)o} \right) \quad \forall (l \backslash l \in \Omega^{L+}) \tag{5}$$

$$p_{lo}^L = x_l^L B_l \left(\theta_{s(l)o} - \theta_{r(l)o} \right) \quad \forall (l \in \Omega^{L+}) \tag{6}$$

$$-F_l^{max} \leq p_{lo}^L \leq F_l^{max} \quad \forall l \backslash l \in \Omega^{L+} \tag{7}$$

$$0 \leq p_{go}^E \leq P_g^{E^{max}} \quad \forall g \tag{8}$$

$$0 \leq p_{do}^{LS} \leq P_d^{D^{max}} \quad \forall d. \tag{9}$$

Limit (11) states load equilibrium of the generated power and the load on each system's bus. Limits related to power flow passing through existing channels and candidate channels are stated in (5) and (6) respectively. The amount of power generated by existing generators is limited by (8).

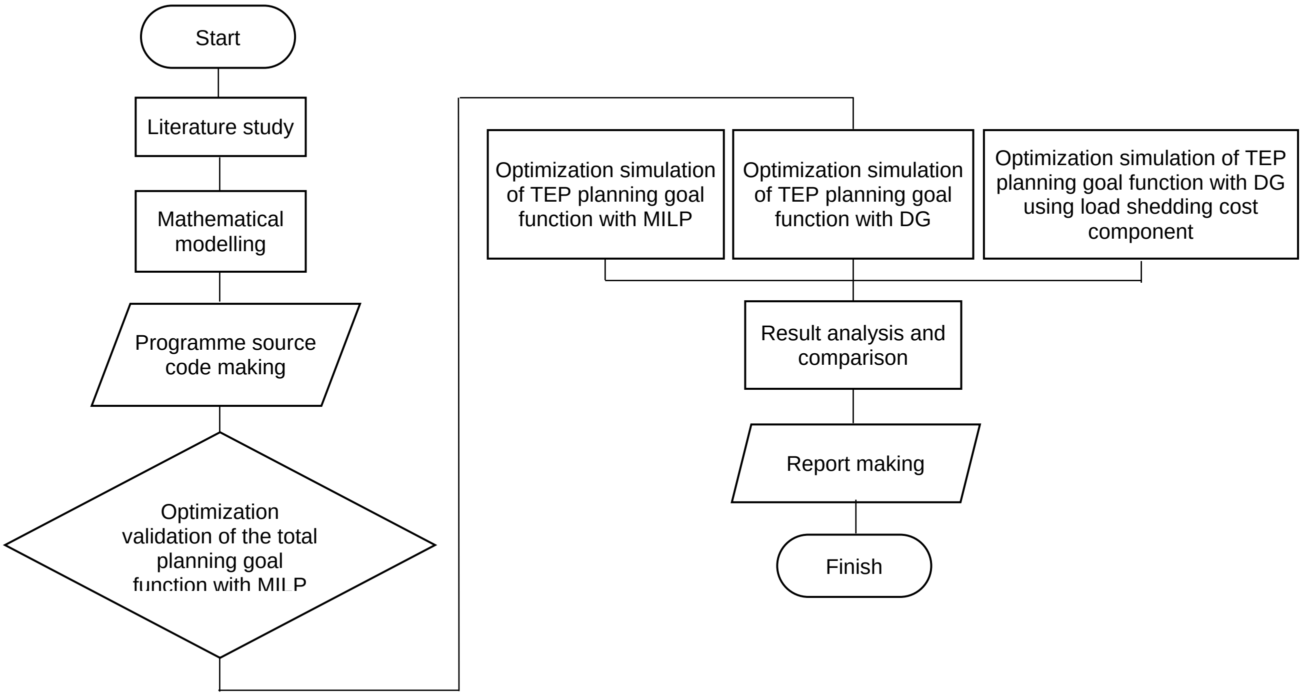

Fig. 1 Research flow diagram.

C. Linearization

TEP model is formulated in the form of MINLP with one non-linear limit. That non-linear limit is (6) in which there is a result between x_l^L and B_l. With a linearization procedure, (6) can be substituted with an equal limit equation stated by (10) and (11). Additional limit must be added in the model with auxiliary variable which must be equal with the result of continuous variable, binary variable, constants, and M is a quite big positive constant.

$$-x_l^L F_l^{max} \le p_{lo}^L \le x_l^L F_l^{max} \quad \forall l \in \Omega^{L+} \tag{10}$$

$$-(1-x_l^L)M \le p_{lo}^L - B_l\left(\theta_{s(l)o} - \theta_{r(l)o}\right) \le (1-x_l^L)M \,. \tag{11}$$

D. DG Implementation in TEP Model

In this model, DG will be implemented as a negative load. In this way, DG will reduce power demand in all buses with its negative load. DG implementation will alter the TEP model objective functions and some limits will also be added. Objective function in (1) must be modified by adding a DG investment as a new part of the equation. Therefore, the objective function will be as seen in (12) in which the DG investment cost component has been included. DG operating costs must also be included in the TEP model objective function and of course that will change the TEP objective function in (1).

$$\min \sum_{o=1}^{no} \rho \left[\sum_{g=1}^{ng} C_g^E p_{go}^E + \sum_{d=1}^{nd} C_d^{LS} p_{do}^{LS} + \sum_{dg=1}^{ndg} C_{dg}^C p_{dgo}^C \right] + \sum_{l \in \Omega^{L+}} \tilde{I}_l^L x_l^L + \sum_{dg \in \Omega^{DG+}} \tilde{I}_{dg}^C p_{dg}^C \,. \tag{12}$$

Some limits must be added into the model due to the influence of DC implementation on all buses with its negative load. The load equilibrium limit in (4) must be modified to improve the load demand as DG installations on the bus. This limit will be seen in (13). This limit will treat DG as a negative load on all buses to reduce local load if some DG will probably be built. Similar to the generator unit, DG capacity is predetermined, therefore the limits for choosing the to be built DG capacity must be added into the TEP model. These limits and some additional limits from linearization result are very similar to previous equation. DG production must be limited to choose DG capacity. This limitation is implemented as a limit in (14). This limit can also be used to develop a scenario with respect to DG penetration level on each bus with load.

$$\sum_{g \in \Omega_n^E} p_{go}^E + \sum_{c \in \Omega_n^E} p_{dgo}^C - \sum_{l|s(l)=n} p_{lo}^L + \sum_{l|r(l)=n} p_{lo}^L = \sum_{d \in \Omega_n^D} \left(p_{do}^{D^{maks}} - p_{do}^{LS} \right) \quad \forall n \tag{13}$$

$$0 \le p_{dgo}^C \le P_{dg}^{C^{max}} \quad \forall c \,. \tag{14}$$

III. METHODOLOGY

This research on DG role analysis towards TEP was carried out based on flow diagram in Fig. 1.

IV. RESULTS AND DISCUSSION

In this part, simulation results are provided and displayed to show the proposed model implementation. The evaluated case study was 6 Bus Graver test system originally published on the previous studies. This test systems can be seen in Fig. 2. Fig. 2 shows existing power system which will be expanded in the future to meet the growing electricity demand. Six new buses will be added into the system to meet the system's total demand. Currently the new buses are not connected in the existing system. Power plant addition and network expansion will be yielded with minimum costs by the proposed model.

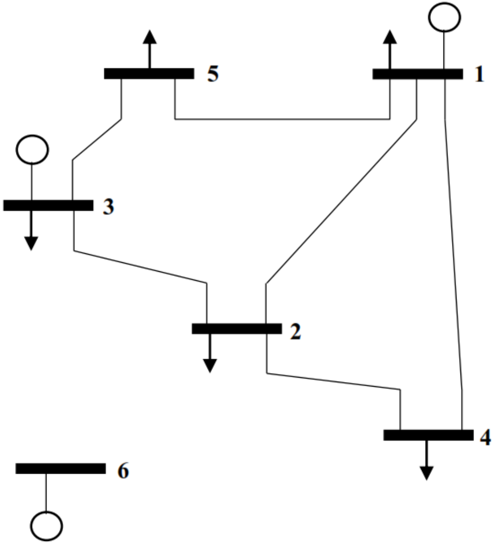

Fig. 2 6-Bus Graver test system.

Generated power data and load requests are now presented in Table I. Demand in every bus is modelled with two operation conditions representing basic load and peak load. Basic load occurs for 6,000 hours and peak load occurs for 2,760 hours in a year. This operation condition will be used to schedule generator unit to meet the demand in each bus. This model uses a DC model, so power losses are not included in this analysis. To meet the future load, additional generating units should be added to the system. However, in the TEP model, it is assumed the existing plant has enough capacity to supply the load demand. Therefore, what needs to be done is a new transmission line addition. Power plant data for 6-Bus system are shown in Table I. The power plant allocation for each bus can be seen on this table. Third column shows power plant allocation on each corresponding bus. Each of the fourth and fifth columns contains information about power plant capacity and electrical power generating cost for each power plant unit.

TABLE I
POWER PLANT UNIT DATA

No.	**Power Plant Unit**	**Bus**	$P_g^{E^{max}}$ **(MW)**	C_g^E **($/MWh)**
1.	g_1	n_1	370	18
2.	g_2	n_3	460	25
3.	g_3	n_6	500	16

Load data on 6-Bus systems are shown in Table II. The third column contains information about load allocation for each bus. While each of the fourth and fifth column contains information about loads on two operating conditions in each bush and the sixth column shows costs associated to load shedding. The load shedding data was an assumption data. Transmission networks planning that will be modelled was based on projected load that will occur. Thus, the load on each of these buses is a representation of the lowest load conditions for the future by taking into account the maximum load expected during the planning period.

TABLE II
LOAD DATA IN 6-BUS GARVER SYSTEM

No.	**Load**	**Bus**	$P_{do2}^{D^{max}}$ **(MW)**	$P_{do2}^{D^{max}}$ **(MW)**	C_d^{LS} **($/MWh)**
1.	d_1	n_1	50	80	70
2.	d_2	n_2	100	240	71
3.	d_3	n_3	25	40	75
4.	d_4	n_4	90	160	85
5.	d_5	n_5	170	240	85

TABLE III
DATA OF TRANSMISSION LINE INSTALLED WITH 6-BUS GARVER SYSTEM

No.	**Load**	**From Bus**	**To Bus**	B_l **(S)**	F_l^{max} **(MW)**
1.	l_1	n_1	n_2	250	100
2.	l_2	n_1	n_4	167	80
3.	l_3	n_1	n_5	500	100
4.	l_4	n_2	n_3	500	100
5.	l_5	n_2	n_4	250	100
6.	l_6	n_3	n_5	500	100

TABLE IV
CANDIDATE DATA OF 6-BUS GRAVER SYSTEM TRANSMISSION LINE

No.	**Load**	**From Bus**	**To Bus**	B_l **(S)**	F_l^{max} **(MW)**	$\tilde{I}_l^L$ **($)**
1.	l_7	n_1	n_3	263	100	3,491,000
2.	l_8	n_1	n_6	147	70	1,951,000
3.	l_9	n_2	n_5	323	100	4,280,000
4.	l_{10}	n_2	n_6	333	100	4,422,000
5.	l_{11}	n_3	n_4	169	82	5,900,000
6.	l_{12}	n_3	n_6	208	100	2,764,000
7.	l_{13}	n_4	n_5	159	75	2,106,000
8.	l_{14}	n_4	n_6	333	100	4,422,000
9.	l_{15}	n_5	n_6	164	100	2,175,000

Table III provides information about transmission line that has been installed in 6-Bus system. Each of the third and fourth column has information about the sender and receiver buses for each transmission line. Each of the fifth and sixth column contains susceptibility values and capacity of each installed transmission line.

From 6-Bus system, there were 9 possibilities that can be carried out for transmission line development. Data for transmission line development can be seen in Table IV, on the third and fourth column. Each of them contains information about sender and receiver buses of each transmission line. Each of fifth and sixth column contains susceptibility values and candidate's capacities of each transmission line. Seventh column contains information about investment costs of each transmission line. In the administered simulation, budget limit available for each year in the transmission network development was $30 million. This budget would set limitation on the number and types of transmission line that will be built.

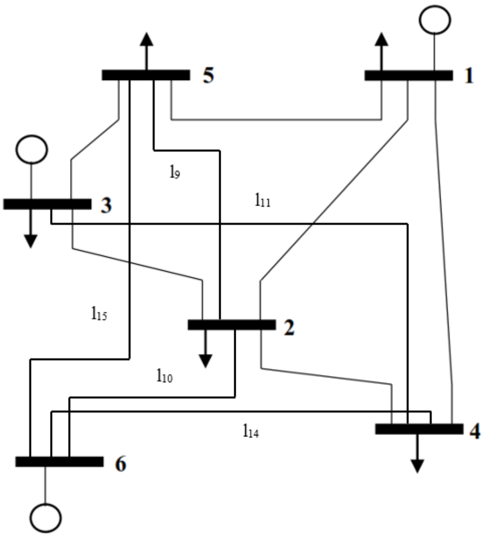

Fig. 3 System configuration after TEP.

A. *TEP Simulation Result without DG*

TEP model optimal completion generated candidate addition of l_8, l_{10}, l_{11}, l_{14} ,and l_{15} transmission line. The result can be seen in Fig. 3. This result caused the system on bus 6 to be interconnected, where the system initial state in bus 6 was separated from power plant unit existing in bus 1 and 3, and most of the loads were in bus 1, 2, 3, 4, and 5. Moreover, power plant unit with cheaper operation cost was in bus 6. It shows that without any transmission line addition, the loads in buses number 1, 2, 3, 4, and 5 were supplied with power plant with more expensive operating costs. Thus, transmission line addition, which connected two areas, was the most optimal solution with some of the loads on buses number 1, 2, 3, 4, and 5 were supplied from power plant with operation cost cheaper than bus 6. Generating unit contribution from bus 6 would also reduce generation costs. The optimal overall cost was $106.4 Million.

TABLE V
INVESTMENT COSTS AND DG OPERATION DATA

DG Technology	P_{dgq}^{Option} **(MW)**	C_{dg}^{DG} **($/kW-month)**	I_{dg}^{DG} **(cost c)**
CT	30	0.024	550,000
DE	45	0.025	350,000

B. *TEP Simulation Result with DG implementation*

As had been described in the model description, the DG would be implemented as a negative load on the system. So, candidates from DG generation units would be located at each load. DG technology that would be considered for construction in this simulation can be seen in Table V. It can be seen from the table that there are two types of DG technologies in the simulation that would be done, the first is *Combustion Turbine* (CT) and the second was *Diesel Engine* (DE). First column shows the DG technology that would be used. The second column shows DG candidates capacity that would be used in simulation. Third column shows DG operating costs and the fourth column shows DG candidates investment costs.

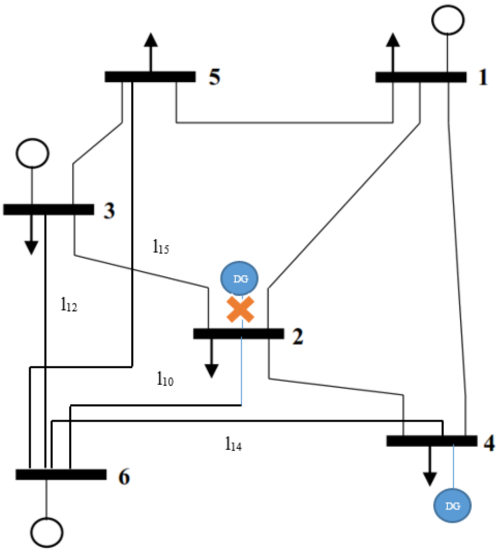

Fig. 4 Systems configuration after TEP with DG.

TEP model simulation result with DG implementation on 6-Bus system is shown in Fig. 4. TEP model optimal completion with DG yielded candidate addition of l_8, l_{10}, l_{14}, and l_{15} transmission lines. Of course, it is different from the results of TEP planning without DG. In this model, l_{11} line was not built due to the existing DG on bus 4. Almost similar to TEP model, the presence of DG also caused the systems on bus 6 to be interconnected, in which the system's initial state in bus 6 was separated from most of generating unit in bus 1 and 3, and most of the loads were in bus 1, 2, 3, 4, and 5. Moreover, power plant unit with cheaper operation cost was in bus 6. It shows that without any transmission line addition, the loads in buses number 1, 2, 3, 4, and 5 were supplied with power plant with more expensive operating costs. Load shedding could occur on buses 1, 2, 3, 4, and 5 which resulted in load shedding costs emergence. DG existence could reduce the Load shedding emergence because DG was located in loads area that certainly reduced the loads, but this scenario did not use load shedding cost components. Thus, transmission line addition with DG, that connected two areas, was the most optimal solution with some of the loads were on bus 1, 2, 3, 4 and 5 being supplied from power plant with operation costs cheaper than from bus 6 and also from DG. Generator unit contribution from bus 6 and DG would also reduce the power generation costs. The optimal overall cost was $103.18 million consisting of $13,783 million for transmission line investment costs and $89,397 for power generation costs.

C. *TEP Simulation Result with DG Implementation with Load Shedding Cost Component*

TEP model simulation results with DG using Load Shedding costs on 6-Bus system are shown in Fig. 5.

Optimal completion of TEP model with DG using load shedding costs component yielded the l_8, l_{10}, l_{14}, and l_{15} transmission lines candidates addition. The result of transmission line addition and TEP model with DG are similar, but by using load shedding cost the DG will not be built in bus 2 or 4. It is because the model will choose the cheapest total planning cost solution, i.e. by paying load shedding costs of 16.416 MW on bus 4. The optimal overall cost was \$100.47 Million consisting of \$13,783 million in transmission line investment costs, \$89,397 million for electricity generation and load shedding costs.

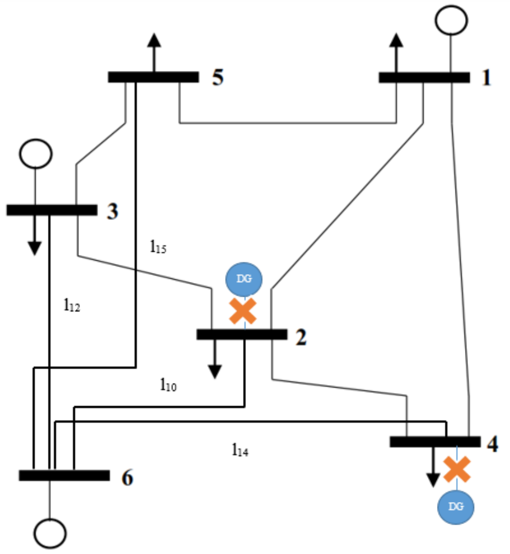

Fig. 5 Simulation results of 6-Bus system with TEP model with DG using load shedding costs.

TABLE VI
ALTERED LOAD SHEDDING COSTS VALUES

No.	Load	C_d^{LS} 1 (\$/MWh)	C_d^{LS} 2 (\$/MWh)	C_d^{LS} 3 (\$/MWh)	C_d^{LS} 4 (\$/MWh)	C_d^{LS} 5 (\$/MWh)
1.	d_1	70	90	95	100	140
2.	d_2	71	110	115	120	142
3.	d_3	75	130	135	140	150
4.	d_4	85	140	145	150	170
5.	d_5	85	140	145	150	170

TABLE VII
LOAD SHEDDING COST COMPONENT SENSITIVITY ANALYSIS RESULTS

No.	Scenario	Total Planning Costs
1.	C_d^{LS} 1	\$100.47 Million
2.	C_d^{LS} 2	\$102.96 million
3.	C_d^{LS} 3	\$103.18 million
4.	C_d^{LS} 4	\$103.18 million
5.	C_d^{LS} 5	\$103.18 million

D. Sensitivity of TEP Simulation Analysis with DP Implementation with Load Shedding Costs Component

Because the load shedding cost was still an assumption, then the sensitivity analysis of load shedding cost component influence was administered by administering running for 5 times on the designed program with load shedding costs data that was altered in accordance with the Table VI.

Those load shedding costs values then were put into the model, the results are as follows. Load shedding costs components would affect overall planning costs when the load shedding costs in the scenario were under C_d^{LS} 3, then for the values above C_d^{LS} 3, the model would not choose to pay the load shedding. Therefore, scenario with the most optimal result was by building DG on bus 4 with overall planning costs of \$ 103.18 million. These results can be seen in Table VII.

V. CONCLUSION

In transmission line addition planning, the 6-Bus Graver system test required 5 additional lines, and this model's optimal value yielded total planning costs of \$ 106.4 millions.

The result of transmission line addition planning with Distributed Generation without load shedding, in the 6-Bus Graver system test, using DG Combustion Turbine (CT) and Diesel Engine (DE) showed that the model would prefer to build DE type DE and build 4 new transmission lines, with a total planning cost of \$103.18 millions.

Load shedding costs component will make total planning costs becomes cheaper if the load shedding costs at the average 5 loads are below \$122/MWh.

Further research will focus on the DG impact towards the system's reliability. DG's impact and load uncertainty can also be added to the model.

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