Ziari, Iman, Ledwich, Gerard, Ghosh, Arindam, & Platt, Glenn
(2011)
Optimal control of distributed generators and capacitors by hybrid DPSO.
In
Ledwich, Gerard (Ed.)
Australasian Universities Power Engineering Conference (AUPEC 2011), 25 - 28 September 2011, Australia, Queensland, Brisbane. (In Press)

Optimal Control of Distributed Generators and Capacitors by Hybrid DPSO

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Abstract - **In this paper, a comprehensive planning methodology is proposed that can minimize the line loss, maximize the reliability and improve the voltage profile in a distribution network. The injected active and reactive power of Distributed Generators (DG) and the installed capacitor sizes at different buses and for different load levels are optimally controlled. The tap setting of HV/MV transformer along with the line and transformer upgrading is also included in the objective function. A hybrid optimization method, called Hybrid Discrete Particle Swarm Optimization (HDPSO), is introduced to solve this nonlinear and discrete optimization problem. The proposed HDPSO approach is a developed version of DPSO in which the diversity of the optimizing variables is increased using the genetic algorithm operators to avoid trapping in local minima. The objective function is composed of the investment cost of DGs, capacitors, distribution lines and HV/MV transformer, the line loss, and the reliability. All of these elements are converted into genuine dollars. Given this, a single-objective optimization method is sufficient. The bus voltage and the line current as constraints are satisfied during the optimization procedure. The IEEE 18-bus test system is modified and employed to evaluate the proposed algorithm. The results illustrate the unavoidable need for optimal control on the DG active and reactive power and capacitors in distribution networks.**

Keywords: distribution network, optimization methods, reliability

I. INTRODUCTION

Minimizing the line loss, maximizing the reliability and improving the voltage profile are the main factors in planning of distribution networks. These aims can be achieved by installing Distributed Generators (DGs) and capacitors along with upgrading the distribution lines. The investment cost of installing and upgrading these elements is an issue which prevents engineers to widely use these technologies. Therefore, a compromise among the investment cost and the benefits should be performed. For this purpose, an optimization technique to allocate and size of DGs, capacitors and distribution lines should be employed.

The optimization techniques are principally categorized into two different methods, analytical methods and heuristic methods. Analytical methods, such as linear, nonlinear and mixed integer programming, are based on derivative of the objective function. Although these methods are quick in finding the global minimum, the need for an initial solution and difficulty in differentiation from various types of nonlinear objective functions are among their disadvantages. An incorrect selection of initial values leads to inaccurate results when these methods are applied. Heuristic methods are based on random values and operators. However these techniques are simple in concept, easy to implement and do not need an initial solution and differentiation from the nonlinear objective functions, the local minimum problem is their main imperfection.

Optimal planning of distribution systems is a discrete and nonlinear problem so its objective function has a number of local minima. In this paper, a heuristic method, called Particle Swarm Optimization (PSO), is modified using the Genetic Algorithm (GA) operators, mutation and crossover. This is performed to increase the diversity of the optimizing variables to decrease the probability of trapping in local minima.

DGs are broadly studied in the literature. These devices are used for improving reliability in particular and the line loss and voltage profile in general. Wang et al [1] propose an analytical method to allocate and size a DG in a distribution network designed to minimize the line loss. Another analytical method is employed in [2] for solving the DG allocation problem. This analytical method is based on the analysis of continuation power flow and the most sensitive bus to voltage collapse. In [3], the optimal location of DGs for minimizing the line loss is determined using a kalman filter. This problem is solved by the ordinal optimization approach in [4]. As a heuristic method, a GA is employed in [5,6] to minimize the line loss, maximize the reliability, and improve the voltage profile by optimal allocation and sizing of DGs. As another heuristic technique, an Ant Colony System (ACS) is employed in [7] to solve the same problem but with inclusion of reclosers.

As much less expensive devices compared with DGs, capacitors are commonly used in distribution networks for minimizing the line loss and improving the voltage profile. The maximum sensitivities selection method is used in [8] for allocation of fixed and switched capacitors in the distribution system as the substation voltage is distorted. In [9,10], GA and a combination of GA and fuzzy logic are employed to find the optimal placement, replacement and sizing of capacitors in a distorted distribution network. Minimum line loss along with an optimal reconfiguration is achieved using the optimal installation of capacitors by another heuristic method, ACS, in [11].

Distribution lines are generally upgraded in a distribution system to support the growing loads. Line upgrading may also be used to decrease the line loss by replacing a line with a lower impedance and higher rated current line.

The above points illustrate the need for a planning technique to include consideration of DGs, capacitors and upgrading distribution lines simultaneously for improving the line loss, reliability and voltage profile in a distribution system. Ultimately, the lowest cost planning is found when all of these technologies are considered.

II. Problem Formulation

Identifying the optimizing variables is the first step in an optimizing procedure. Figure 1 shows the structure of optimizing variables in the planning problem.

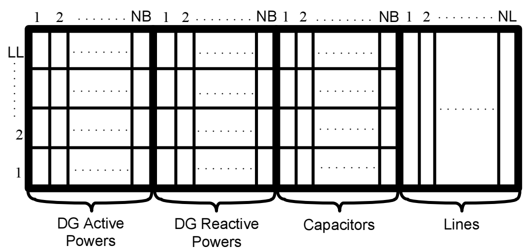

Figure 1. The structure of a particle

As shown in this figure, the optimizing variables are composed of the injected active and reactive power of DGs at different buses for different load levels, the size of installed capacitors at different buses for different load levels, the type of distribution lines, and the tap setting of HV/MV transformer for different load levels. The HV/MV transformer tap is also set.

The objective function is composed of the investment cost of DGs, capacitors and distribution lines, the line loss cost and the reliability cost. The bus voltage and the line current as constraints are included in the objective function using a constraint penalty factor. The objective function is formulated as follows:

$$OF = C_{CAP} + C_{PL} + C_T + \sum_{y=0}^{Y} \frac{1}{(1+r)^y} (C_{O\&M} + C_L + C_I) + DP \tag{1}$$

where OF is the objective function which is the net present value of the total cost, C_{CAP} is the total capital cost for DGs and capacitors, $C_{O\&M}$ is the total operation and maintenance (O&M) cost for DGs and capacitors, C_{PL} is the peak loss cost, C_T is the HV/MV transformer upgrading cost, C_L is the loss cost, C_I is the interruption cost, r is the discount rate, DP is the constraint penalty factor, and Y is the number of years in the study timeframe.

The installation cost of DGs and capacitors are assumed to be proportional to their rating. The O&M cost of capacitors depends on their rating and the study timeframe. The O&M cost of DGs depends on the fuel cost and their working time durations. The interruption cost is calculated using (2).

$$C_I = \sum_{t=1}^{T} \begin{cases} \sum_{l=1}^{NL} k_E \times P_{L,l}^t \times (RT - DGT) & S_{DG,l} \geq P_{L,l}^t \\ \sum_{l=1}^{NL} k_E \times \begin{bmatrix} (P_{L,l}^t - S_{DG,l}) \times RT + \\ S_{DG,l} \times (RT - DGT) \end{bmatrix} & S_{DG,l} < P_{L,l}^t \end{cases} \tag{2}$$

where T is the number of load levels, NL is the number of distribution lines, k_E is the cost per kWh, $P_{L,l}^t$ is the total power of under outage loads at load level t when a fault occurs at line l, $S_{DG,l}$ is the total rating of DGs available to supply the loads under outage due to a fault at line l, RT is the average time for repairing a line after a fault, and DGT is the average time for running a DG.

The loss cost and the peak loss cost are calculated using as detailed in equations (3) and (4).

$$C_I = \sum_{t=1}^{T} k_E \times D_t \times PLoss_t \tag{3}$$

$$C_{PL} = k_P \times PLoss_T \tag{4}$$

where D_t is the duration of load level t, $PLoss_t$ is the total loss at load level t, and k_P is the cost per MW for supporting the distribution system at the peak load level.

The constraints are formulated as shown in (5) and (6). The bus voltage (V_{bus}) should be maintained within the standard level.

$$0.95\ pu \leq V_{bus} \leq 1.05 \tag{5}$$

The line current (I_f) should be less than the line rated current (I_f^{rated}).

$$I_f \leq I_f^{rated} \tag{6}$$

The DG output power as the final constraint should be more than 30% of the rated power.

III. Implementation of HPSO

A. Overview of PSO

As a population-based and self-adaptive technique, PSO was introduced originally by Kennedy and Eberhart in 1995 [12]. In this optimization method, a population of individuals searches for the optimal solution in parallel. The individuals are called *particles* and the population is called a *swarm*. Each particle in the swarm moves towards the optimal point with an adaptive velocity. $X_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,n})$ and $V_i = (v_{i,1}, v_{i,2}, \ldots, v_{i,n})$ are used to represent the position and velocity of particle i

in an n-dimensional vector. The best solution related to each particle during its movement is called personal best and is represented by $Pbest_i=(pbest_{i,1}, pbest_{i,2}, \ldots, pbest_{i,n})$ and the best solution obtained by any particle in the neighbourhood of that particle is called global best and is denoted as $Gbest=(gbest_{i,1}, gbest_{i,2}, \ldots, gbest_{i,n})$. The velocity and position of particles are updated during an iterative procedure [13,14].

DPSO, as a discrete version of PSO, is employed in this paper. This is based on rounding off the optimizing variables, the particle position, to the nearest integer value. In [14], it is concluded that the performance of DPSO is not influenced in this rounding compared with the other methods. In this paper, the DPSO is modified by GA operators to increase the diversity of the optimizing variables in order to decrease the risk of trapping in local minima.

B. Applying Hybrid PSO

Before beginning the optimization procedure, the optimizing variables need to be identified (Figure 1). Each block in this figure shows an optimizing variable. The value of the corresponding member is the size of capacitors or DGs in a load level or the line types. A threshold is assigned for each block. If the value of this member is more than the specific threshold, it indicates that an element with the corresponding size is installed at the corresponding bus. Otherwise, no element is placed at that bus. This specific threshold is the minimum size of the available set of capacitors/DGs or the primary line type. For example, assume the value of the block in row 3 and column 4 in the capacitor part is 300. This means a capacitor with the size of 300 kVAR is installed at bus 4 for third load level.

Figure 2 shows the flowchart of the proposed HDPSO. The description and comments of the steps are presented as follows.

Step 1. (Input System Data and Initialization)

In this step, the optimization method parameters are determined including the number of population members and iterations as well as the PSO weight factors. The population of particle positions X_j and velocities V_j in the search space are randomly initialized. The distribution network configuration and data and the available capacitors, DGs, and conductors are input. The maximum allowed voltage drop and the characteristics of conductors, impedance and rated current, are also specified.

Step 2. (Calculate the Objective Function)

Determined from the previous step, the size and location of DGs and capacitors in different load levels and the line types are used to reconstruct the admittance matrix. This new admittance matrix is used in a load flow to calculate the bus voltages, line currents, and the distribution line loss for each load level. The reliability cost is computed based on the location and rating of DGs. These are substituted in (1) to constitute the objective function. The constraints are also evaluated using (5) to (6) in this step. The "death penalty" method is used in this paper to include the constraints. In this method, the constraints are included in the objective function with a penalty factor, called *DP*, in (1). If all constraints are satisfied, *DP* will be zero. Otherwise, *DP* is set as a large number and is added to the objective function to exclude the relevant solution from the search space [15].

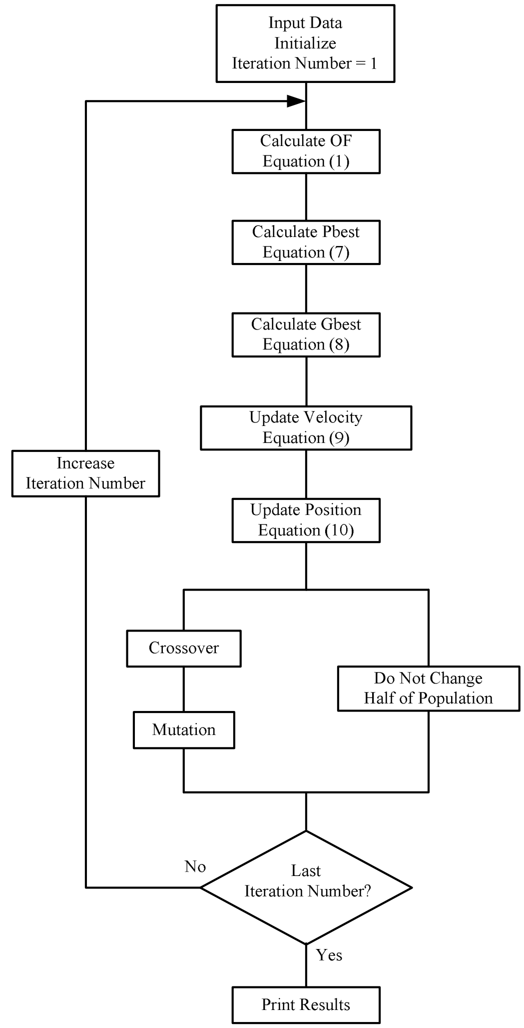

Figure 2. Algorithm of proposed PSO-based approach

Step 3. (Calculate pbest)

The objective function value associated with a particle is compared with the corresponding value in previous iteration and the position with lower objective function is recorded as *pbest* for the current iteration.

$$pbest_j^{k+1} = \begin{cases} pbest_j^k & \text{if } OF_j^{k+1} \geq OF_j^k \\ x_j^{k+1} & \text{if } OF_j^{k+1} \prec OF_j^k \end{cases} \quad (7)$$

where k is the number of iterations, and OF_j is the objective function component evaluated for particle j.

Step 4. (Calculate gbest)

In this step, the lowest objective function among all of *pbest*s in the current iteration is compared with those in the previous iteration and the lower one is labeled as *gbest*.

$$gbest^{k+1} = \begin{cases} gbest^k & if\ OF^{k+1} \geq OF^k \\ pbest_j^{k+1} & if\ OF^{k+1} \prec OF^k \end{cases} \quad (8)$$

Step 5. (Update position)

The velocity of particles for the next iteration is calculated using the current *pbest* and *gbest* as follows:

$$V_j^{k+1} = \omega V_j^k + c_1\, rand(\, pbest_j^k - X_j^k\,) + c_2\, rand(\, gbest_j^k - X_j^k\,) \quad (9)$$

where V_j^k is the velocity of particle *j* at iteration *k*, ω is the inertia weight factor, c_1 and c_2 are the acceleration coefficients, X_j^k is the position of particle *j* at iteration *k*, $pbest_j^k$ is the best position of particle *j* at iteration *k* and $gbest^k$ is the best position among all particles at iteration *k*.

As observed in (9), ω is to adjust the effect of the velocity in the previous iteration on the new velocity for each particle. Regarding the velocity of each particle obtained in (9), the position of particles can be updated for the next iteration using (10):

$$X_j^{k+1} = X_j^k + V_j^{k+1} \quad (10)$$

Step 6. (Apply GA Operators)

In this step, half of the population members continue DPSO procedure and the other half goes through the GA operators. The crossover and mutation operators are used in this paper to be applied to the second half of the population members. These two operators apply random changes to the optimizing variables which results in increasing the diversity of the optimizing variables so decreasing the risk of trapping in local minima.

Step 7. (Check convergence criterion)

If $Iter = Iter_{max}$ or if the output does not change for a specific number of iterations, the program is terminated and the results are printed, else the programs goes to step 2.

IV. RESULTS

To validate the proposed technique, the IEEE 18-bus distribution system [9,10] is used. The ideal distribution line in this system is replaced with practical lines in order to access their rated current. The load duration curve is approximated by three load levels (160%, 100%, and 50% of the average load) to decrease the computation time. However, a sensitivity analysis will be performed in the future work to find the optimal load level number. It is assumed that the duration of these three load levels is 15%, 55% and 30% of a year.

To highlight the necessity of planning in presence of all technologies, five different scenarios are studied. Upgrading of distribution lines is studied in the first scenario. The capacitors are planned in the second scenario. To improve these two scenarios, an integrated planning in which both of the capacitors and lines are upgraded is investigated in the third scenario. As a new technology, DGs are optimally allocated and sized in the fourth scenario. These are combined with the use of capacitors and line upgrades in the fifth scenario. During these procedures, the transformer tap for different load levels is optimized.

A. First Scenario

As a conventional planning, the line loss and the voltage profile are improved by upgrading the distribution lines. The line number is in this order, the line between buses, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 2-9, 1-20, 20-21, 21-22, 21-23, 23-24, 23-25, and 25-26.

It should be noted that the distribution lines are primarily in types (6-5-5-4-1-1-1-1-3-2-1-2-1-1-1). The characteristics of the available conductors are given in the appendix (Table A). After applying the proposed HDPSO, the optimal solution shows an upgrade in the lines to (9-9-9-7-3-1-1-1-6-5-1-2-1-1-1). This means the first five distribution lines should be upgraded from types 6, 5, 5, 4, and 1 to types 9, 9, 9, 7, and 3, respectively. Furthermore, the ninth and tenth lines should be upgraded from types 3 and 2 to 6 and 5. This upgrading applies more than 1 million dollars investment cost. The HV/MV transformer tap is set on 0.981, 0.993, and 1.03 for the lowest to peak load level. Additionally, an HV/MV transformer upgrade (from 25 kVA to 35 kVA) needs to be performed to support the loads.

B. Second Scenario

The optimal placement and size of capacitors for different load levels are determined in this scenario. It is observed that 7 capacitors with the rating of 2400, 1950, 900, 900, 900, 1350, and 1650 are to be installed at buses 3, 4, 5, 7, 10, 15, 16, respectively. The optimal capacitors and the transformer tap setting for different load levels are given in Table I.

TABLE I. THE CAPACITORS FOR DIFFERENT LOAD LEVELS (KVAR)

Load Level	**Bus Number**							**Tap**
	3	**4**	**5**	**7**	**20**	**25**	**26**	
1	0	150	750	600	0	900	0	0.994
2	0	750	900	600	900	1050	0	1.00
3	2400	1950	900	900	900	1350	1650	1.026
Fixed	0	150	750	600	0	900	0	
Switched	2400	1800	150	300	900	450	1650	

As observed in this table, 4 fixed capacitors and 7 switched capacitors are found as the optimal solution. No transformer upgrading is required in this scenario.

C. Third Scenario

In this scenario, the techniques mentioned in the first and second scenarios are integrated. The optimal placement and size of capacitors along with upgrading of the distribution lines are included in this scenario. It is resulted that the lines should be upgraded to (9-9-5-4-3-1-1-1-6-6-1-2-1-1-1). This means that the line upgrading cost is reduced from 1.1134 to 0.8283 M$ compared with the first scenario. Table II demonstrates the optimal capacitor at different buses and the transformer tap setting for different load levels.

TABLE II. THE CAPACITORS FOR DIFFERENT LOAD LEVELS (KVAR)

Load Level	**Bus Number**							**Tap**
	4	**5**	**6**	**7**	**20**	**25**	**26**	
1	300	0	1350	150	0	0	600	0.984
2	300	150	1350	600	0	0	600	0.984
3	300	150	1350	900	750	1050	750	1.013
Fixed	300	0	1350	150	0	0	600	
Switched	0	150	0	750	750	1050	150	

The optimal solution is to install 4 fixed capacitors and 5 switched capacitors. The fixed capacitors are located at buses 4, 6, 7, and 26 with sizes 300, 1350, 150, and 750 kVAR, respectively. The switched capacitors are located at buses 5, 7, 20, 25, and 26 with sizes 150, 750, 750, 1050, and 150 kVAR, respectively. As observed, the total capacitor sizes are reduced from 10050 to 5250 kVAR compared with scenario 2. Similar to the second scenario, no transformer upgrading is required.

D. Fourth Scenario

DG planning is implemented in this scenario to study this technology in distribution system planning. The optimal location and output power of DGs along with the HV/MV transformer tap setting for different load levels are illustrated in Table III.

TABLE III. THE DG OUTPUTS FOR DIFFERENT LOAD LEVELS (KVA)

Load Level	**Bus Number**		**Tap**
	8	**25**	
1	0	0	1.030
2	0	0	1.030
3	3000	3000	1.030

It can be seen that 2 DGs should be located at buses 8 and 25. The injected power of these DGs for the load levels less than the peak load is zero because the output power of a generator has been assumed not to be less than 30% of its rated power in order to maximize the efficiency of that generator. In this case, the 25 kVA transformer does not need to be upgraded like scenarios 2 and 3.

E. Fifth Scenario

All technologies are included in this scenario for planning a distribution system in order to increase the reliability and voltage profile and decrease the line loss. The optimal solution shows that the lines should be upgraded to (9-9-9-4-1-1-1-1-5-2-1-2-1-1-1) which applies 0.5913 M$ investment cost for line upgrading (compared with 1.1134 M$ and 0.8283 M$ in scenarios 1 and 3). The optimal location and output power of DGs and capacitor sizes for different load levels are given in Tables IV and V.

Three fixed and eight switched capacitors should be installed at the distribution system in this final solution. The optimal solution for DGs is to allocate one DG at bus 26. The output power of this DG is 1.712 MVA which means that its practical rating should be 1.8 MVA. A significant decrease is observed in the DG investment cost in this case (1.0936 M$) compared with the previous case (4.8735 M$).

TABLE IV. THE CAPACITORS FOR DIFFERENT LOAD LEVELS (KVAR)

Load Level	**Bus Number**									
	2	**4**	**5**	**6**	**7**	**9**	**20**	**22**	**25**	**26**
1	0	0	0	750	0	0	0	600	0	900
2	900	1050	1050	1500	450	750	900	600	450	900
3	900	1050	1050	1650	450	1050	900	600	450	900
Fixed	0	0	0	750	0	0	0	600	0	900
Switched	900	1050	1050	900	450	1050	900	0	450	0

TABLE V. THE DG OUTPUTS FOR DIFFERENT LOAD LEVELS (KVA)

Load Level	**Bus Number**	**Tap**
	26	
1	0	0.989
2	0	0.997
3	1712	1.015

Similar to scenario 4, the output power of the installed DG is zero for all load levels rather than the peak level. This is because of the DG output power constraint which is not allowed to be less than 30% of its rated power. Similar to scenarios 2 to 4, no upgrading is required for the HV/MV transformer.

F. Comparison of Scenarios

In this section, the above five scenarios are compared together and with the case in which no installation and upgrading is performed (Table VI). This comparison is based on the constituting parts of the objective function, the investment cost of lines, DGs, capacitors, and transformer, the line loss cost and the reliability cost.

TABLE VI. COMPARISON OF TOTAL COST DURING 20 YEARS (M$)

Cost Elements	**No Installation**	**Scenario Number**				
		1	**2**	**3**	**4**	**5**
Line Cost	0	1.1134	0	0.8283	0	0.5913
Capacitor Cost	0	0	0.4241	0.2405	0	0.4213
DG Cost	0	0	0	0	4.8735	1.0936
Transformer Cost	2.2589	2.2589	0	0	0	0
Loss Cost	3.1749	1.7684	2.6390	1.7818	2.7659	2.1684
Reliability Cost	14.942	14.942	14.942	14.942	10.054	13.183
Total Cost	20.376	20.083	18.005	17.792	17.693	17.457

The total cost is a good factor to compare all configurations. The total cost associated with the 'no installation' case is not feasible because the bus voltage constraint is not satisfied. As observed in Table VI, the lowest cost planning and the highest cost planning belong to the proposed technique and the first scenario, respectively. As a conventional planning, first scenario applies 15% (2.919 M$) higher cost compared with the proposed technique. The next low cost planning technique is when DGs, as a new technology, are employed. As observed, using DGs significantly reduces the reliability cost (10.054 M$ in scenario 4 compared with 14.942 M$ in scenarios 1 to 3). This highlights the main benefit of DGs which is improving the reliability of a distribution system. On the other hand, DG planning is not as appropriate as the line upgrading for minimizing the line loss so that the loss cost in scenarios 1 and 3 is about 1 M$ lower than the fourth scenario. Capacitors have a remarkable influence on both line loss and voltage profile. Moreover, they are efficient to avoid upgrading the HV/MV transformer. These points reveal that the lowest cost planning is implemented when all of these technologies are included to deal with the planning problem.

V. Conclusion

An integrated planning is proposed to optimal control of the injected power of DGs and capacitors. The distribution line and HV/MV transformer upgrades are included during the planning procedure. The HV/MV transformer tap is controlled based on the load level.

HDPSO is employed in this paper to solve the planning problem. This technique is a modified version of DPSO in which two GA operators, mutation and crossover, are applied to half of the population members. This is performed to increase the diversity of the optimizing variable in order to reduce the risk of trapping in local minima, which is often the main drawback in heuristic methods. The objective function in this method is composed of the investment cost of DGs, capacitors, and distribution lines, the line cost and the reliability cost. The cost of HV/MV transformer upgrading is also included in this function. The bus voltage and the line current as constraints are added to the objective function using a penalty factor.

The IEEE 18-bus distribution system is used to evaluate the proposed configuration. A comparison is performed among different planning techniques. The results reveal the necessity of planning. Furthermore, it is demonstrated that the lowest cost planning is realized when the proposed integrated planning is employed and all available technologies are included for solving the planning problem.

VI. Acknowledgment

This work was supported by the Australian Research Council (ARC) and Ergon Energy through the ARC linkage Grant LP 0560917 and through the CSIRO Energy Transformed Flagship.

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VIII. Appendix

Table A show the characteristics of the available conductors.

TABLE A. Characteristics of The Available Conductors

Conductor Type	R (Ω)	X (Ω)	I (A)
1	1.05	0.295	187
2	0.465	0.270	307
3	0.291	0.225	409
4	0.198	0.240	517
5	0.139	0.227	642
6	0.108	0.220	747
7	0.0897	0.213	837
8	0.0730	0.206	949
9	0.0634	0.201	1034
10	0.0584	0.197	1284