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# A modified harmony search based method for optimal rural radial line planning

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**Abstract**

Long medium voltage radial lines are usually used to supply power to large areas with a very low population/ load density. Generally, the planning of this kind of lines involves both continuous and discrete variables, or in other word, this problem is a mixed integer programming one. Many available algorithms may experience difficulties in solving this kind of problems. In this work, a Harmony Search (HS) based optimization approach is developed to solve the radial line planning problem. Furthermore, some modifications to the HS are presented for improving the computational efficiency of optimization problems with strongly interrelated mixed variables. A sample system is served for demonstrating the feasibility and effectiveness of the proposed approach.

*Key words:* radial line planning, harmony search, mixed integer programming; radial line planning

## 1. Introduction

Power system planning is generally a complicated nonlinear multi-objective optimization problem with different kinds of constraints. The difficulty of solving this problem stems from the large number of optimization variables involving both continuous and discrete types. The planning objective is to determine the most economical scheme with security constraints respected. As it is difficult for traditional mathematical optimization methods to solve the planning problem efficiently, many different approaches based on Artificial Intelligence (AI) such as Tabu Search (TS), Genetic Algorithm (GA) and Differential Evolution (DE), have been proposed for this purpose in the past decade.

TS is a restricted neighbourhood search technique with the guidance of the flexible memory of the search history. Due to its good performance, many TS based approaches have been developed for a wide variety of optimization problems in power systems such as fault section estimation (Wen *et al*, 1997), transmission network optimal planning (Wen *et al*, 1997) and optimal placement of capacitors in radial distribution systems (Yang *et al*, 1995). These applications have shown the high efficiency of TS in handling combinatorial optimization problems. In principle, TS based methods are more suitable for 0-1 integer programming problems. However, many practical optimization problems cannot be formulated as such. GA represents a computational technique mimicking the concept of the biological evolution process (Goldberg, 1989). Up to now, there have been an enormous number of GA applications for solving difficult optimization problems (Carpimelli *et al*, 2001; Huang and Negnevitsky, 2008; Samaan and Singh, 2004). The major advantages of GA lie in its adaptability to many kinds of problems and its speed in obtaining optimal solutions, but its encoding requirement limits its efficient applications in some problems (Dong *et al*, 2006). DE is reported to be superior to GA and Evolutionary Strategy (ES) in solving the power system planning problem. DE is an evolutionary algorithm similar to GA, while its ability to operate on floating-point variables makes it more flexible. Furthermore, some modifications for DE are made to better cater for the need of the planning problems (Dong *et al*, 2006; Yang *et al*, 2008; Lampinen and Zelinka, 1999). However, up to now, there is not a definite conclusion on how to well handle the planning problem involving different kinds of variables.

In this work, Harmony Search (HS) is employed to solve the optimal rural radial line planning problem. HS was proposed several years ago, and has been successfully applied in a wide variety of optimization problems with good convergence performances. The rural radial line planning problem, an instance of the more general distribution system planning problem, is illustrated to verify the efficiency of the developed approach. Line selections and the placements of voltage regulators (including the decisions regarding whether and where voltage regulators should be installed) are taken into account. Moreover, the placement of a voltage regulator is regarded as a whole, called a mixed variable, in the process of searching for the optimal solution. To make HS suitable for handling mixed variables defined in this work, some modifications to HS are also made.

In Section 2, the traditional HS is briefly described. The formulation of the rural line planning problem is given in Section 3. In Section 4, the specific modifications of HS for the mixed variables involved in the rural line planning is presented. A sample system is employed for demonstrating the feasibility and efficiency of the developed HS based approach in Section 5. Finally, the conclusion is presented in Section 6.

## 2. The basic principles of harmony search

The Harmony Search (HS) algorithm was originally proposed by GEEM Z W in 2001 (Geem *et al*, 2001). HS is a novel meta-heuristic search method, mimicking the improvisation process of music players, and utilizing just one solution vector for each search (Geem *et al*, 2001) (Lee and Geem, 2005). Up to now, it has been successfully employed in a wide variety of areas including power systems such as the combined heat and power economic dispatch (Vasebi *et al*, 2007), power control strategy of parallel inverters (Baghaee *et al*, 2008) and fault current reduction in distribution systems with distributed generation units (Baghaee *et al*, 2008).

To describe the working procedure of HS, an optimization problem is specified as follows:

$$\min\ F(\mathbf{X})$$

$$X=[X_{con}, X_{dis}]=[x_1,x_2,\cdots,x_i\cdots x_n]$$

Subject to:

$$x_i^L \le x_i \le x_i^U$$

where $\mathbf{X}$ is a $n$-dimension vector composed of optimization variables to be determined, and its any element $x_i$ may be continuous ($\boldsymbol{X}_{con}$) or discrete ($\boldsymbol{X}_{dis}$). F($\mathbf{X}$) is the objective function; $x_i^U$ and $x_i^L$ respectively denotes the upper and lower bounds of $x_i$. The nomenclatures used in the HS algorithm are as follows.

***HM***: harmony memory. A list in which some solution vectors are included, and sorted by their corresponding values of the objective function.

***HMS***: harmony memory size. It represents the number of solution vectors (i.e., optimization variables) in HM.

***Memory Consideration***: It is used to choose the value for a certain element of the new vector from the specified HM range.

***Pitch Adjustment***: It is used to adjust the value of the component obtained by the memory consideration according to a specified strategy.

***Random Selection***: It is used to select one value randomly for a certain element of the new vector from the possible range of values.

***HMCR***: harmony memory considering rate.

***PAR***: pitch adjusting rate.

***bw***: an arbitrary distance bandwidth.

As shown in Fig. 1, HS is mainly composed of three steps: initialization, new solution generation and updating operation.

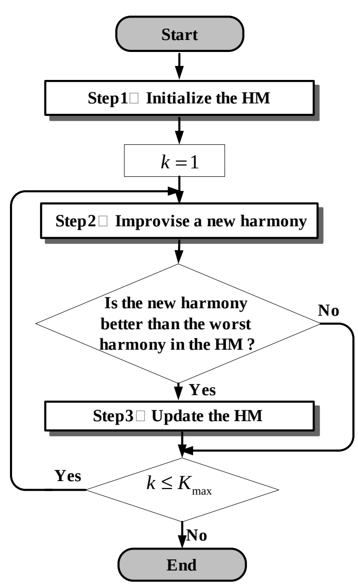


**Fig.1 The optimization procedure of the HS algorithm**

The HS algorithm is carried out by the following steps:

**Step 1** Initialize the Harmony Memory (*HM*).

Similar to most existing meta-heuristic algorithms, in HS a random rule is also employed to generate the initial solution vector.

$$x_i = \begin{cases} x_i^L + r_{and} \times (x_i^U - x_i^L) & x_i \text{ is continuous} \\ x_i^L + \lfloor r_{and} \times (x_i^U - x_i^L) \rfloor & x_i \text{ is discrete} \end{cases} \tag{1}$$

Where $\lfloor \bullet \rfloor$ denotes rounding down to the nearest integer. $r_{and}$ is a random number uniformly distributed between 0 and 1. At the end of this step, the *HM* list is filled with randomly generated solution vectors.

**Step 2** Improvise a new harmony

A new harmony vector, $X^{'} = [x_1^{'}, x_2^{'}, ..., x_N^{'}]$, is generated according to the following three rules:

- Memory Consideration
- Pitch Adjustment
- Random Selection

For instance, $x_i^{'}$, the value of the *i*th optimization variable in the new vector, is generated in accordance with the memory consideration with a probability of *HMCR*, while (1-*HMCR*) is the rate of selecting one value by the random selection. The component obtained by the memory consideration is adjusted with the rate of *PAR*. If the pitch adjustment is carried out, $x_i^{'}$ is replaced as follows:

$$x_i^{'} = \begin{cases} x_i^{'} \pm r_{and} \times bw_i & x_i \text{ is continous} \\ x_i^{'} \pm \lfloor r_{and} \times bw_i \rfloor & x_i \text{ is discrete} \end{cases} \tag{2}$$

where $bw_i$ is a distance bandwidth of the *i*th variable in the new vector.

As described above, the pitch adjustment and random selection are primarily responsible for maintaining the diversity of solutions and for searching the new territory, while the memory consideration serves to improve the convergence performance. It is a disadvantage of the traditional HS algorithm to use fixed values for both *PAR* and *bw*. In early iterations (generations), small *PAR* and large *bw* could lead the HS algorithm to increase the diversity of solution vectors, while large *PAR* and small *bw* are usually helpful for improving the best solution in the final iteration stage. Given this background, an improved HM algorithm (Mahdavi *et al*, 2007) is presented with adaptable *PAR* and *bw* as follows:

$$\begin{cases} c = \dfrac{\ln(\dfrac{bw^L}{bw^U})}{K_{\max}} \\ bw\ (k) = bw^U \times e^{(c \times k)} \\ PAR(k) = PAR_{PA}^L + \dfrac{(PAR^U - PAR^L)}{K_{\max}} \times k \end{cases} \tag{3}$$

where

$K_{\max}$ is the permitted maximum number of generations, i.e., stopping criterion;

$bw^L \le bw \le bw^U$ and $PAR^L \le PAR \le PAR^U$ .

As shown in Fig.2, *PAR* and *bw* change dynamically with the increase of the generation (iteration) number.

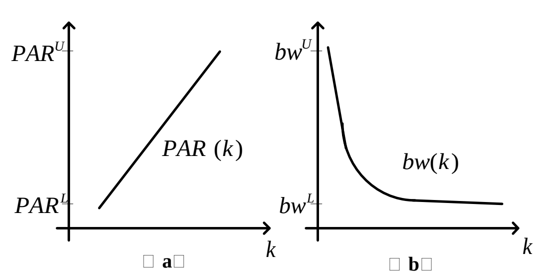


**Fig. 2 The variation of *PAR* and *bw* with the increase of the generation number**

**Step 3** Update the *HM*

If the new vector generated in Step 2 is better than the worst harmony in the *HM* in terms of the corresponding objective function values, the new vector is then added in the HM and the existing worst harmony is excluded from the *HM*.

HS has the advantage of ease to be implemented, powerful capability at finding areas of the global optimum and at using mathematical techniques for fine-tuning within those areas. Its effectiveness in solving nonlinear constrained optimization problems has been proven in many applications (Kim *et al*, 2001) (Geem *et al*, 2002) (Kang and Geem, 2004).

## 3. The mathematic model for rural radial line planning

In some developed countries, long medium voltage radial lines are widely employed to supply power to large areas with very low population and load density. As the lines are normally very long, voltage regulators are usually used to mitigate the voltage dropping problem and hence the placements of voltage regulators should be taken into account in the planning procedure. In this work, the line selections and placements of voltage regulators are of primary concern. Fig. 3 displays the typical topology of a rural radial line with $K$ loads evenly distributed along the feeder.

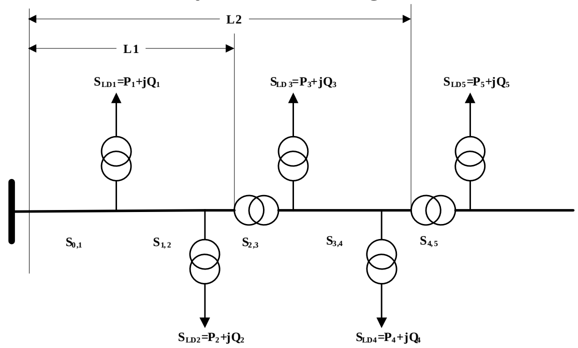


**Fig.3 The typical topology of a rural radial line**

Based on the given topology structure, the planning problem can be regarded as an issue of selecting appropriate values for the design parameters as stated below:

$$\begin{cases} \mathbf{B} = \{b_1,\ b_2, \cdots b_i, \cdots, b_N\} \\ \mathbf{L} = \{L_1, L_2, \cdots L_i \cdots, L_N\} \\ \mathbf{S} = \{S_{0,1}, S_{1,2}, \cdots S_{n-1,n} \cdots, S_{K-1,K}\} \end{cases} \tag{4}$$

where

**B** and **L** are both $N$-dimension vectors with $N$ being the maximum permitted number of voltage regulators;

$b_i$, the $i$th element of **B**, is a 0-1 variable, and represents whether the $i$th voltage regulator should be installed or not (1 or 0);

$L_i$, the $i$th element of **L**, is a continuous variable between zero and the total length of the line, and represents the location of the $i$th voltage regulator;

**S** is a $K$-dimension vector with $K$ being the total number of loads;

$S_{n-1,n}$, the $n$th element of **S**, is a discrete variable, and identifies the selected type of cables for the section between the *(n-1)*th and $n$th loads.

In fact, if the $i$th voltage regulator is not selected for installation ($b_i$=0), then it will not be necessary to determine $L_i$, i.e., the designed parameters $b_i$ and $L_i$ are interrelated. In most AI based methods, the design parameters are considered separately. In this work, $\mathrm{M}_i$, a new type variable called the mixed variable, is defined to combine two related design parameters $b_i$ and $L_i$ as follows:

$$\mathrm{M_i} = [b_i \mid L_i]$$

$\mathrm{M}_i$ is treated as a single variable like a continuous one. The corresponding modification of HS will be introduced in the next section to deal with this mixed variable. Then, the solution vector **X** can be expressed as follow:

$$\mathbf{X} = \{\mathbf{M}, \mathbf{S}\} = \{M_1, M_2, \cdots M_N, S_{0,1}, S_{1,2} \cdots S_{K-1,K}\} \tag{5}$$

The objective of the radial line planning is to reduce the total cost under given security constraints. Issues of installation cost, line loss and physical constraints all affect the design-making process. In this paper, the mathematical formulation of the rural line planning problem is as follows:

$$Min\ \ F(\mathbf{X}) = C_{RV}(\mathbf{X}) + C_C(\mathbf{X}) + C_{PL}(\mathbf{X}) \tag{6}$$

Subject to

$$\begin{cases} V_{\min} \le V_n \le V_{\max} \\ I_{n-1,n} \le \mathrm{I}_{\max} \end{cases}$$

where $F(\mathbf{X})$ represents the total cost consisting of the installation cost, i.e., the cost of voltage regulators ($\mathrm{C_{RV}}(\mathbf{X})$) and that of cables ($C_C(\mathbf{X})$)), and the cost line losses ($C_{PL}(\mathbf{X})$). The detailed formulas for calculating these costs are as follows:

$$\begin{cases} C_{RV}(\mathbf{X}) = A \times T \\ C_C(\mathbf{X}) = \sum_{n=1}^{K} \frac{l}{K} \times W(S_{n-1,n}) \\ C_{PL}(\mathbf{X}) = \sum_{i=0}^{Y} \left( (P_L \times C_L \times H \times f) / (1+p)^i \right) \end{cases} \tag{7}$$

where

$A$ is the cost of each voltage regulator;

$T$ is the maximum possible number of voltage regulators to be installed;

$l$ is the total length of the line;

$W(S_{n-1,n})$ is the cost of per unit length of the selected line between the ($n$-1)th and $n$th loads;

$P_L$ is the power loss at the peak load point (kW), and can be approximated by calculating the power loss per section of the line between two loads;

$C_L$ is the cost of per kW losses;

$H$ is the hours per year (=8760h);

$Y$ denotes the number of years to accumulate the losses;

$f$ is the load factor.

Taking the time value of funding into account, the cost of power loss in the $i$th year should be transferred to its present value with annual rate $p$.

## 4. Modifications of HS for rural radial line planning

In this section, the modifications to the traditional HS will be detailed so as to deal with the defined mixed variable in the last section. The modifications are mainly concerned with the processes of initialization and improvisation.

First, the formulas used for the HM initialization are modified as follows:

$$M_i(b) = \begin{cases} 1, \text{ if } \mathrm{r}_{and} < 0.5 \\ 0, \text{ else} \end{cases}$$
$$M_i(L)' = \begin{cases} M_i(L)^L + \mathrm{r}_{and} \times (M_i(L)^U - M_i(L)^L), \text{ if } M_i(b) = 1 \\ \text{null, else} \end{cases} \tag{8}$$

It is not clear that why using harmony search instead of other algorithms.

As shown in Eqn. (8), if the $i$th voltage regulator is not selected for installation ($M_i(b) = 0$), then the location of this regulator is no longer an issue to consider ($M_i(L) = \text{null}$). These initialization strategies are consistent with the practical situations.

Secondly, in order to utilize the available information for the placements of voltage regulators in the current HM more reasonably, $b_i$ and $L_i$ are regarded as a whole in this work. Given this background, the following modifications for improvisation are presented. If $\mathrm{r}_{and} < HMCR$, $M_i'$, the parameter corresponding to the $i$th regulator in the new solution vector, is generated by the memory consideration in Eqn. (9) below, otherwise randomly according to Eqn. (8). For the pitch adjustment in handling mixed variables, the modifications are defined in Eqn. (10).

$$M_i' = M_{i,n} \tag{9}$$

$$\begin{cases} M_i'(b) = M_{i,n+\text{step}}(b) \\ M_i'(L) = M_{i,n+\text{step}}(L) + \mathrm{r}_{and} \times \text{bw} \end{cases} \tag{10}$$

where

$M_{i,n}$ denotes the $i$th element of the $n$th solution vector saved in the current $HM$;

$n$ is generated randomly between 0 and ($HMS$-1) (memory consideration).

To apply the pitch adjustment on the mixed variable, *step*, a randomly generated integer, is added to $n$ with the constraint $0 \le n + step \le HMS - 1$.

## 5. Test results

In this section, a long medium voltage radial line with 50 loads evenly distributed along the feeder will be employed as a test system to verify the feasibility and effectiveness of the proposed planning method. The details of the test system are detailed below:

- A radial system will be designed to supply power for 50 loads.
- The loads are evenly distributed along the feeder, each with its own MV/LV supply transformer.

- Each load is 10 kVA with the power factor 0.85 lagging (under the peak load condition).
- 7 different candidate overhead conductors are specified, each with a different cross sectional area (and hence R & X) and cost (as shown in Table 2).
- The maximum permitted number of installed voltage regulators is 3; each can boost the voltage by a maximum of 10%. The cost of each voltage regulator is known.
- Different conductors could be employed for different sections along the line (between loads).
- The constraint on the voltage at each customer connection point is within ±6% of the nominal voltage, i.e. $0.94 \leq V \leq 1.06$.

The available data are respectively listed in Table 1 and Table 2.

**Table 1 Parameters for the planning**

| Parameter | $C_L$ | $Y$ | $f$ |
|---|---|---|---|
| Value | $0.076/kWh | 20 y | 0.333 |

**Table 2 Parameters of candidate lines**

| | Cable Name | Cost [$/km] | Maximum Current [A] | R [Ohm/km] | X [Ohm/km] |
|---|---|---|---|---|---|
| 1 | GZ 3/2.75 | 500 | 49 | 11 | 0.45 |
| 2 | AC 2/2.75 | 720 | 76 | 5 | 0.45 |
| 3 | Quince | 800 | 85 | 4.37 | 0.346 |
| 4 | Raisin | 1200 | 131 | 2.14 | 0.324 |
| 5 | Sultana | 1500 | 181 | 1.21 | 0.302 |
| 6 | Libra | 1900 | 237 | 0.6 | 0.284 |
| 7 | Mercury | 3100 | 388 | 0.26 | 0.259 |

**22kV 3-phase system planning**

The planning for a 22kV 3-phase system is carried out. The simulation results are listed in Table 3 and Table 4, and the total cost is $1807679.24.

**19.1kV Single Wire Earth Return planning**

The single wire earth return (SWER) or single wire ground return is usually used to supply single-phase electrical power from an electrical grid to remote areas at a low cost. The planning for a 19.1kV SWER is tested here. The planning results are listed in Table 3 and Table 4, and the total cost is $999351.98.

## 6. Conclusions

In this work, a modified HS based method is developed for the planning problem. The capability of HS in handling constrained optimization problems with a large number of variables of different types has been demonstrated with many application examples. For the given rural line planning problem, a new type mixed variable is defined to deal with the voltage regulator placement problems more reasonably. Furthermore, some modifications for HS are made so as to make it more efficient for the rural radial line planning problem. The obtained optimal solution can satisfy the power flow and other physical constraints with low costs. In fact, the modified HS is applicable to many practical optimization problems in different areas.

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**Table 3 The planning results on line selections**

| Line Number | 22 kV 3-phase system | | | 19.1 kV SWER | | |
|---|---|---|---|---|---|---|
| | Connected Nodes (Unit: kV) | | Cable Name | Connected Nodes (Unit: kV) | | Cable Name |
| 1 | 0 | 1/21.926 | Mercury | 0 | 1/19.012 | Libra |
| 2 | 1 | 2/21.853 | Libra | 1 | 2/18.967 | Mercury |
| 3 | 2 | 3/21.781 | Libra | 2 | 3/18.922 | Mercury |
| 4 | 3 | 4/21.653 | Sultana | 3 | 4/18.768 | Raisin |
| 5 | 4 | 5/21.525 | Raisin | 4 | 5/18.686 | Libra |
| 6 | 5 | 6/21.490 | Mercury | 5 | 6/18.644 | Mercury |
| 7 | 6 | 7/21.368 | Raisin | 6 | 7/18.500 | Sultana |
| 8 | 7 | 8/21.334 | Mercury | 7 | 8/20.212 | Raisin |
| 9 | 8 | 9/21.217 | Raisin | 8 | 9/20.143 | Libra |
| 10 | 9 | 10/21.155 | Libra | 9 | 10/20.108 | Mercury |
| 11 | 10 | 11/21.044 | Raisin | 10 | 11/19.988 | Sultana |
| 12 | 11 | 12/20.935 | Raisin | 11 | 12/19.871 | Sultana |
| 13 | 12 | 13/20.829 | Raisin | 12 | 13/19.808 | Libra |
| 14 | 13 | 14/22.884 | Mercury | 13 | 14/19.696 | Raisin |
| 15 | 14 | 15/22.834 | Libra | 14 | 15/19.332 | Quince |
| 16 | 15 | 16/22.744 | Raisin | 15 | 16/19.225 | Raisin |
| 17 | 16 | 17/22.659 | Sultana | 16 | 17/19.121 | Raisin |
| 18 | 17 | 18/22.613 | Libra | 17 | 18/19.067 | Libra |
| 19 | 18 | 19/22.532 | Sultana | 18 | 19/18.969 | Sultana |

**Table 3 (cont'd) The planning results on line selections**

| Line Number | 22 kV 3-phase system | | | 19.1 kV SWER | | |
|---|---|---|---|---|---|---|
| | Connected Nodes (Unit: kV) | | Cable Name | Connected Nodes (Unit: kV) | | Cable Name |
| 20 | 19 | 20/22.489 | Libra | 19 | 20/18.875 | Sultana |
| 21 | 20 | 21/22.467 | Mercury | 20 | 21/18.783 | Sultana |
| 22 | 21 | 22/22.445 | Mercury | 21 | 22/18.735 | Libra |
| 23 | 22 | 23/22.374 | Sultana | 22 | 23/18.649 | Raisin |
| 24 | 23 | 24/22.304 | Raisin | 23 | 24/18.603 | Libra |
| 25 | 24 | 25/22.268 | Libra | 24 | 25/18.523 | Raisin |
| 26 | 25 | 26/22.232 | Libra | 25 | 26/18.446 | Sultana |
| 27 | 26 | 27/22.027 | Quince | 26 | 27/18.372 | Raisin |
| 28 | 27 | 28/21.967 | Sultana | 27 | 28/18.333 | Libra |
| 29 | 28 | 29/21.910 | Raisin | 28 | 29/18.296 | Libra |
| 30 | 29 | 30/21.856 | Raisin | 29 | 30/20.094 | Libra |
| 31 | 30 | 31/21.804 | Raisin | 30 | 31/20.037 | Raisin |
| 32 | 31 | 32/21.754 | Raisin | 31 | 32/19.893 | Raisin |
| 33 | 32 | 33/21.707 | Raisin | 32 | 33/19.956 | Libra |
| 34 | 33 | 34/21.694 | Mercury | 33 | 34/19.907 | Raisin |
| 35 | 34 | 35/21.534 | AC2/2.75 | 34 | 35/19.862 | Raisin |
| 36 | 35 | 36/21.495 | Sultana | 35 | 36/19.819 | Sultana |
| 37 | 36 | 37/21.355 | AC2/2.75 | 36 | 37/19.780 | Sultana |
| 38 | 37 | 38/21.321 | Raisin | 37 | 38/19.638 | AC2/2.75 |
| 39 | 38 | 39/21.312 | Mercury | 38 | 39/19.604 | Sultana |
| 40 | 39 | 40/21.216 | Quince | 39 | 40/19.484 | AC2/2.75 |
| 41 | 40 | 41/21.116 | AC2/2.75 | 40 | 41/19.375 | AC2/2.75 |
| 42 | 41 | 42/21.037 | Quince | 41 | 42/19.349 | Raisin |
| 43 | 42 | 43/20.956 | AC2/2.75 | 42 | 43/19.273 | Quince |
| 44 | 43 | 44/20.886 | AC2/2.75 | 43 | 44/19.200 | Quince |
| 45 | 44 | 45/20.870 | Raisin | 44 | 45/19.196 | Libra |
| 46 | 45 | 46/20.826 | Quince | 45 | 46/19.182 | Raisin |
| 47 | 46 | 47/20.816 | Raisin | 46 | 47/19.171 | Sultana |
| 48 | 47 | 48/20.813 | Quince | 47 | 48/19.138 | AC2/2.75 |
| 49 | 48 | 49/20.793 | AC2/2.75 | 48 | 49/19.119 | Quince |
| 50 | 49 | 50/20.776 | Quince | 49 | 50/19.099 | AC2/2.75 |

**Table 4 The planned results on voltage regulators**

| | 22 kV 3-phase system | | 19.1 kV SWER | |
|---|---|---|---|---|
| | Installed or not ? | Site | Installed or not ? | Site |
| 1 | Yes | 44.1km | Yes | 29.7km |
| 2 | No | / | Yes | 120.9km |
| 3 | No | / | No | / |

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