A Study on a Centralized Under-Voltage Load Shedding Scheme Considering the Load Characteristics

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Abstract

Under-voltage load shedding is an important measure for maintaining voltage stability. Aiming at the optimal load shedding problem considering the load characteristics, firstly, the traditional under-voltage load shedding scheme based on a static load model may cause the analysis inaccurate is pointed out on the equivalent Thevenin circuit. Then, the dynamic voltage stability margin indicator is derived through local measurement. The derived indicator can reflect the voltage change of the key area in a myopia linear way. Dimensions of the optimal problem will be greatly simplified using this indicator. In the end, mathematical model of the centralized load shedding scheme is built with the indicator considering load characteristics. HSPPSO is introduced to solve the optimal problem. Simulation results on IEEE-39 system show that the proposed scheme display a good adaptability in solving the under-voltage load shedding considering dynamic load characteristics.

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Keywords: voltage stability; under-voltage load shedding; load characteristic; voltage stability margin indicator; Centralized scheme; HSPPSO

1. Introduction

With the expanding scale of the power grid and development of power market, system operation is running to its limit. Frequency of voltage collapse occurrence is increasing. In recent years, several worldwide voltage collapse accidents has forced the scholars from various countries focus on the severe social impact and economic losses caused by it. A quick and timely identification of the system's emergency state and take measures to prevent voltage collapse has important meaning. Voltage stability control measures are usually conservative and expensive, but automatic load shedding as an important measure for voltage stability is drawing more and more attention for its effectiveness and low costs.
Choose an appropriate location and amount can not only improve the efficiency of optimal load shedding but also significant for the system stability. Considering the traditional under-voltage load shedding usually based on the operators’ experience, scholars had a depth study of optimal LS to improve its low efficiency in recent years.

Literature[1] takes the distance between the trajectory of operation system and the singular surface as the sensitivity criterion, by load shedding to face away from the singular system trajectory, thus ensuring system stability, time-consuming, load static model becomes the method's shortcomings.

A static voltage stability considering the sensitivity of load-shedding method is proposed in literature[2], it is based on a voltage instability risk index, by calculating the the of sensitivity load index on each node to determine the location of load-shedding, but the method is based on a static model without considering the system dynamics. To determine the best load shedding strategy, minimum mismatch function is used in reference[3]. To achieve the desired accuracy, the proposed method requires application of PV curve which increases the calculation process and is not conducive to online calculation. By parameterize the control strategy, literature[4] is looking for a new equilibrium point after under-voltage load shedding for the system, but the minimum LS amount is unavailable especially when voltage of the midpoint in the system is minimum or a local reactive power is short in the area. Literature [5] achieved under-voltage load shedding based on extended fuzzy theory. A new under-voltage load shedding strategy is proposed in reference[6] based on risk analysis. But a in-depth study is needed in the the development of indicators and quantitation of the risk.

Although the literature above[1]-[6] presented various method of load shedding schemes, the load model used in them are static, the effect of load shedding caused by dynamic models is ignored. And they are far away from the actual system conditions, lacking of convincing application in practice. Meanwhile, all of the load shedding strategy is distributed thinking, which means the device is installed independently at each node and takes action in accordance with the established index value and delay. Such strategy has an obvious flaw: Each LS location can be independent of the other, lacking of communication. It is conducted to maintain the voltage stability of the load bus or local area and can not serve for the deployment whole system. The indicators for distributed load shedding strategy are usually single and does not consider load characteristics, taking action alone to determine the system voltage instability often leads to malfunction.

Based on this, the Voltage Stability Margin Index ($V_{SML}$) considering the load characteristics is derived on the node’s equivalent Thevenin circuit. The index can be obtained by local measurement information in real-time and show the margin of the the critical region in the voltage change in a myopia linear way. Thus, dimensions of the optimal load shedding problem considering the dynamic model is reduced by using it. Then the mathematical model of the centralized strategy of UVLS is formed with the $V_{SML}$. At last, HSPPSO is introduced to solve the model.

2. The new voltage stability margin indicator

2.1 The effect of load characteristics on voltage stability margin

![Fig.1 The equivalent Thevenin circuit of load buses](image_url)
Fig.1 shows a Equivalent Thevenin circuit of load bus[7].

Where:

- $E_S$ and $Z_S$ the equivalent Thevenin voltage source and impedance
- $V_{LD}$ and $Z_{LD}$ voltage of the load bus and the load impedance

From the basic knowledge of the circuit, it is easy to get:

\[ V_{LD} = \frac{1}{\sqrt{A}} \frac{Z_{LD}}{Z_s} E_s \quad (1) \]

\[ P_L = \frac{Z_{LD}}{A} \left( \frac{E_s}{Z_s} \right)^2 \cos \phi \quad (2) \]

\[ S_L = \frac{1}{A} \left( \frac{E_s}{Z_s} \right)^2 Z_{LD} \quad (3) \]

Where:

\[ A = 1 + \left( \frac{Z_{LD}}{Z_s} \right)^2 + 2 \left( \frac{Z_{LD}}{Z_s} \right) \cos (\theta - \phi) \quad (4) \]

Fig.2 presents $P_L$-$V_{LD}$ curve under different load characteristics, assuming that $E_S=1$, which makes the results very general. In the formula, $\alpha=0-\Phi$.

It is easy to get that the load characteristics has a great influence on voltage stability, the optimization ideas[3] of UVLS based on static load model should continue to explore. As in Fig.2, different $\alpha$ corresponds to different maximum load capability. But the Traditional voltage stability margin index[8] does not take care of the characteristics above, which may lead to a further deterioration of the system operating conditions.

2.2 Derivation of $V_{SMI}$

For voltage stability analysis considering load characteristics, the new voltage stability index based on the local measurement information is derived as follows. If, for the equivalent circuit given in Fig.1, one calculates the derivative of apparent load power against the load admittance, the following result is obtained by formula (3):

\[ \frac{dS}{dY} = \frac{V_{LD}^2 \left( 1 - \left( \frac{Z_s}{Z_{LD}} \right)^2 \right)}{1 + \left( \frac{Z_s}{Z_{LD}} \right)^2 + 2 \left( \frac{Z_s}{Z_{LD}} \right) \cos \alpha} \quad (5) \]

If both sides of the equation are divided by the value of $V_{LD}$, one gets:
\[
\frac{dS}{dY} \cdot \frac{Y}{S} = \frac{1 - (Z_s / Z_{ld})^2}{1 + (Z_s / Z_{ld})^2 + 2(Z_s / Z_{ld}) \cos \alpha}
\] (6)

Though formula(6), one gets:

\[
Z_{ld} = \frac{K + 1}{-K \cos \alpha + \sqrt{(K \cos \alpha)^2 - K^2 + 1}}
\] (7)

where:

\[
K = \frac{dS}{dY} \cdot \frac{Y}{S}
\] (8)

Considering the change of load is always continuous, the factor K can be obtained by the local measurement information directly:

\[
k = \frac{dS}{dY} \cdot \frac{Y}{S} = \frac{S_2 - S_1}{S_1 + S_2} \left( \frac{Y_2 + Y_1}{Y_2 - Y_1} \right)
\] (9)

where:

\[S_1, Y_1\] and \[S_2, Y_2\] load, admittance at measured at \[t_1\] and \[t_2\]

Combined with formula(1), the new voltage stability margin index(V_{SMI}, Voltage Stability Margin Index) considering the load characteristics can be defined as follows based on the local measurement information:

\[
V_{SMI} = f\left( \frac{Z_{ld}}{Z_s}, \alpha \right) = \sqrt{\frac{1}{1 + K^2 + 2K \cos \alpha} - \eta}
\] (10)

In the formula \(\eta\) is the voltage margin threshold considering the way of voltage regulation and load characteristics of the bus. It is easy to figure out that \(V_{SMI}\) considering load characteristics can be simply calculated based on the local measurements and it is short time-consuming through the above process. Fig.3 shows the relationship between \(V_{SMI}\) and the voltage amplitude under different load characteristics.

As it presented in Fig.3, the new index can point out the voltage change of the key area([0.8-1.1] p.u.) in a myopia linear way under different load characteristics. By this way, the shortcomings of the traditional load margin index \(\lambda\) is overcomed. That means the derived index is more smooth and there is no sudden inflection in the whole process.

3. Mathematical description of the centralized scheme

3.1 Mathematical model

The proposed centralized scheme optimize the LS buses and amount in the view of the whole system’s voltage stability after a centralized processing of the system’s information collected. Load shedding is carried out based on the following mathematical model.

The objective function:

\[
\text{Min}\left( \sum_{i=1}^{N} \Delta P_{Di} \right)
\] (11)
Where: $N_K$ is the set of buses for load shedding; $\Delta P_{Di}$ is the shedding amount at bus-$i$. When $V_{SMi}$ is introduced into the model, there is:

$$\Delta P_{Di} = K \frac{1}{d} \int_{S}^{E} (V_{SMi}^{max} - V_{SMi}) \, dt$$  \hspace{1cm} (12)

Subject to:

$$P_{gi}^{0} - P_{gi}^{0} + \Delta P_{Di} = \sum_{j=1}^{N} |V_j||V_j|Y_{ij} \cos(\delta_j - \delta_i)$$  \hspace{1cm} (13)

$$Q_{gi}^{0} - Q_{gi}^{0} + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_j||V_j|Y_{ij} \sin(\delta_j - \delta_i)$$  \hspace{1cm} (14)

$$P_{gi}^{C} - P_{gi}^{C} + \Delta P_{Di} = \sum_{j=1}^{N} |V_j||V_j|Y_{ij} \cos(\delta_j - \delta_i - \delta_C)$$  \hspace{1cm} (15)

$$Q_{gi}^{C} - Q_{gi}^{C} + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_j||V_j|Y_{ij} \sin(\delta_j - \delta_i - \delta_C)$$  \hspace{1cm} (16)

$$V_{SMi}^{min} \leq V_{SMi} \leq V_{SMi}^{max} \quad i \in N_i$$  \hspace{1cm} (17)

$$V_{SMi}^{min,C} \leq V_{SMi} \leq V_{SMi}^{max,C} \quad i \in N_i$$  \hspace{1cm} (18)

$$|P_i| \leq P_i^{max} \quad \forall ij \in \text{lines}$$  \hspace{1cm} (19)

$$|P_i^{C}| \leq P_i^{max,C} \quad \forall ij \in \text{lines}$$  \hspace{1cm} (20)

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad i \in N_G$$  \hspace{1cm} (21)

$$\Delta P_{Di}^{min} \leq \Delta P_{Di} \leq \Delta P_{Di}^{max} \quad i \in N_D$$  \hspace{1cm} (22)

In which: $V_{SMi}^{min}$, $V_{SMi}^{max}$ present the minimum and maximum value of $V_{SMi}$ at bus $i$ according to its load characteristics. Variables with superscript ‘0’ represent the system at normal condition and before any contingencies occur, while ‘C’ represent the variables after LS. The main purpose of the objective function is to minimize the interruption costs while static voltage securities (formula 13&14) as well as dynamic voltage stability constraints (formula 15&16) are simultaneously met. In addition, it is assumed that the slack generator will compensate the network losses while the active power outputs of other generators are kept constant.

3.2 Solution Procedure

According to the characteristics of the established model, this paper selected HSPPSO to solve it. It draws on the hierarchical control theory ideas. It uses a variety of parallel computing cluster particle swarm in the first layer, equal to increasing in the number of particles and expanding the scope of the space in which the particles can be searched. In the second layer, each swarm of the first layer is seen as a particle, and the optimal value of the swarm is seen as the current optimal value of the individual particles.
for the particle swarm optimization. And feedback the global optimal solution obtained in optimization results to the first layer. This will not only improve the efficiency of the optimization algorithm and the convergence of the algorithm, but also be applicable to large-scale system optimization application[9-13].

Specific solution procedure is shown in Figure 4.

Fig.4 Solving procedure based on HSPPSO

4. Simulation Results

A large number of studies have shown that the mathematical model of load can significantly affect the conclusions of system analysis. To demonstrate the derived voltage stability margin index \( V_{SMI} \)'s adaptability to different load characteristics and taking into account a large number of induction motor load in actual system. Definition of the load characteristics at the load buses in IEEE-39 system is shown in Fig.5.

![Fig.5 Simplified model of the load and its equivalent circuit](image)

The model defined is obviously a dynamic load model that including induction motor load and constant impedance load in parallel. In which: \( Z_R \) is the impedance of constant load; \( M \) represents induction motor load; \( R_1, X_1 \) is the stator resistance and reactance; \( R_2, X_2 \) the rotor resistance and reactance; \( s \) is the slip; \( X_p \) the rotor leakage reactance.

Scenario I  Sustainable growth of load
Tab.1 shows the first six load buses that have the smaller $V_{SMI}$ value and $I_{SDVS}$ (voltage stability index presented in reference[14]) in the scenario of load increasing to 1.4p.u. on the same system model. In which, $\eta$ at each node is defined as the value corresponding to the node voltage 0.9p.u. considering load characteristics, and the generator is considering the classic model.

Tab.1 the node voltage stability margin index in Load growth mode

<table>
<thead>
<tr>
<th>Node</th>
<th>$V_{SMI(1.0p.u.)/I_{SDVS}}$</th>
<th>Node</th>
<th>$V_{SMI(1.4p.u.)/I_{SDVS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/7</td>
<td>1.87/4.25</td>
<td>7/7</td>
<td>0.88/2.33</td>
</tr>
<tr>
<td>8/8</td>
<td>2.08/4.73</td>
<td>16/16</td>
<td>0.903/3.57</td>
</tr>
<tr>
<td>4/4</td>
<td>2.11/4.81</td>
<td>27/18</td>
<td>1.012/4.65</td>
</tr>
<tr>
<td>15/15</td>
<td>2.14/5.79</td>
<td>18/24</td>
<td>1.017/4.71</td>
</tr>
<tr>
<td>16/16</td>
<td>2.23/5.90</td>
<td>3/3</td>
<td>1.133/5.47</td>
</tr>
<tr>
<td>3/3</td>
<td>2.66/6.02</td>
<td>24/15</td>
<td>1.402/5.96</td>
</tr>
</tbody>
</table>

Notice: in the Node column of the table, on the left side of sign ‘/’ is the nodes corresponding to $V_{SMI}$ indicators and the right corresponding to $I_{SDVS}$.

In Tab.1, both the two indicators are able to instruct the lower voltage margin buses in the system under normal operating conditions. But under the heavy load condition (1.4p.u.), there is some difference. That is because the proposed index in literature [14] changes in a clearly nonlinear way in the vicinity of voltage collapse point. In this way, a more powerful proof of that this indicator can instruct the margin in a linear way in different load characteristics is shown.

**Scenario II Fault**

Lots of the buses in the system are running to their limit under heavy load conditions, as is shown in Tab.1. To reflect the global optimization ability on voltage stability of the proposed centralized load shedding scheme. Assume that the line between 16 and 19 had a short circuit at 12 cycle under Scenario I, at 22 cycle the line was cut out. The voltage curve of the 6 nodes in Tab.1 is shown in Fig.6.

In Fig.6, there is no action taken after fault. The voltage keeps falling down for the large amount of induction motor loads in the system after the line is cut out. Voltage stability constraints of the nodes are broken, the centralized scheme is triggered to maintain the voltage stability of the system. Optimal solution of load shedding considering the load characteristics is shown in Tab.2.
Tab.2 optimal results of the load shedding problem

<table>
<thead>
<tr>
<th>Node</th>
<th>LS Amount (MW)</th>
<th>Node</th>
<th>LS Amount (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>43.9</td>
<td>23</td>
<td>20.1</td>
</tr>
<tr>
<td>4</td>
<td>13.7</td>
<td>24</td>
<td>17.3</td>
</tr>
<tr>
<td>7</td>
<td>30.6</td>
<td>25</td>
<td>3.9</td>
</tr>
<tr>
<td>8</td>
<td>40.4</td>
<td>26</td>
<td>5.3</td>
</tr>
<tr>
<td>12</td>
<td>0.7</td>
<td>27</td>
<td>30.6</td>
</tr>
<tr>
<td>15</td>
<td>53.8</td>
<td>28</td>
<td>12.3</td>
</tr>
<tr>
<td>16</td>
<td>70.4</td>
<td>29</td>
<td>6.5</td>
</tr>
<tr>
<td>18</td>
<td>40.1</td>
<td>31</td>
<td>2.9</td>
</tr>
<tr>
<td>20</td>
<td>96.3</td>
<td>39</td>
<td>11.4</td>
</tr>
<tr>
<td>21</td>
<td>30.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After the actions were taken, voltage curve of the 6 nodes in the fault is shown in Fig. 7. It is easy to find out that after the load shedding scheme, voltage of the 6 nodes is restored to normal. The proposed centralized LS scheme does work under the dynamic load model.

5. Conclusions

Load characteristics is of considerable influence on system voltage stability, the traditional method based on static load model may be counter productive in the actual use. This shortcoming is pointed out on the equivalent Thevenin circuit while a new voltage stability margin index considering load characteristics is introduced. And a centralized LS scheme is built with it. Simulations on IEEE-39 system shows, the derived indicator can instruct the voltage change of the key area [0.8 p.u.-1.1 p.u.] in a myopia linear way. Dimensions of the optimal problem is greatly simplified. And it is based on local measurement information which makes the calculation online possible.

References


