OPERATION SITUATIONAL AWARENESS BASED ON DYNAMIC POWER FLOW FOR A PROFOUND ANALYSIS OF ACTIVE DISTRIBUTION NETWORK

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ABSTRACT

Operation characteristics of active distribution network (ADN) has become more and more complicated since increasing uncertainties and variable scenarios are introduced with the integration of intermittent distributed energy sources (DERs). An effective novel method is needed to reveal intrinsic characteristics of ADN more precisely and deeply, which traditional analysing methods may not apply any more. A method of operation situational awareness under steady state based on dynamic power flow for ADN is proposed in this paper examining grid's operation status in time-changing scenarios. Key indexes reflecting operation situation are defined and used for a profound analysis. The essence of the proposed dynamic power flow (DPF) method is about continuously allocating unbalanced active power by adjusting energy storage system (ESS) according to consecutive scenario variations when DER integrated. With the result dynamic power flow provides, key indexes can thus be calculated utilizing proposed method. So it is able to analyse current status and predict in which direction the system may possibly move in short terms. Through case study, it shows that the proposed operation situational awareness method can better reflect the status of ADN under the circumstances of strong uncertainties and frequent disturbances than that of traditional method. This will be of help for decision-making process in optimization and control issues.

INTRODUCTION

In the context of power systems, situational awareness (SA) remains obvious technological features as its common conceptual framework describes including data acquisition, cognition and processing, comprehension and prediction [1]. SA technology ought to be used to tackle with complexity problem of modern smart grid. An effective, adequate and precise SA method can provide valuable decision-making support based on which the network operator can take certain measures such as topology transformation, distributed generator dispatching, demand response management and so forth, accomplishing the goal of optimal operation.

It reviews the fundamentals of SA and then discusses supporting key information techniques and tools along with standards that can help improve the level of SA [1]. Also, a generic procedure for achieving sufficient SA is presented, which aims to guide the design of an information system that is both technology and user oriented. A Markova model is adopted to simulate and discuss how do errors in SA affect the operational decision-making process under grid fault conditions [2]. The model is tested on a standard IEEE 24 buses system. It illustrates basic concept of SA in power systems and operation trajectory [3]. The overall goal of automatic smart dispatching with its functionality and technique framework is proposed. Reference [4] initially discusses the design of situation diagrams and how it may directly affect visualization effects of smart awareness. Related research of SA visualization can also be reviewed [5]. Besides, there are sufficient research works focusing on security situation awareness in the field of computer science and internet network technology. Thus, SA technology and application in the domain of smart grid still need to be further studied and explored.

As for the main topic of this paper, traditional analysing methods generally focus on the calculation and evaluation of operation state only on a single time section, which fail to determine the dynamic system's variations within a continuous time process. Obviously, the problem of increased uncertainties, variable scenarios and disturbances in ADN makes it difficult for traditional method to come out with accurate and profound results.

The apply of situational awareness to ADN plays a vital role in obtaining and predicting the operation trajectory. Thus, situational awareness and analysis of operation state based on a kind of dynamic power flow method proposed in this paper is used to solve the problem. Changing scenarios are designed on selected study case. Effectiveness of the proposed method is demonstrated and verified.

KEY INDEXES OF OPERATION SITUATION

Commonly used network total active power loss is one of the most important operation situation indexes. This index, represented by P_{loss}, can be directly adopted to describe grid's basic operation status without self-definition or modification. It can be expressed as follow.

$$P_{loss} = \sum_{i=1}^{n} U_i \sum_{j\in i} U_j G_{ij} \cos\theta_{ij} \tag{1}$$

U_i stands for voltage amplitude at node i, n for the total node number of network, G_{ij} for the conductance of branch line ij, θ_{ij} for phase angle difference of node i and j.

Node voltage variations usually differs from each other in operation. A sort of index which can reflect overall deviation level of node voltage to the required standard nominal value is needed. Thus the index D_V representing voltage deviation rate of system's nodes is defined and given below in (2).

$$D_V = \left(\sqrt{\sum_{i=1}^{n-1}(1-U_i)^2} \Big/ n-1\right)\times 100\% \tag{2}$$

In this index, 1 represents the nominal value of each node voltage in per unit. Apart from the slack node, which is the connection point at substation's low voltage bus outline and its voltage amplitude remains the nominal value and unchanged, all the other nodes in the network are contained in this index. It reflects the system's overall voltage deviation level with the impact of stochastic output of DERs and increased disturbances.

It is obvious that formula (3) holds at any time according to system's power balancing equations. $P_{SL}^{(t)}$ stands for active power injection of slack bus at specified time section *t*. $\sum_{i=1}^{n-1}P_{iDER}^{(t)}$ and $\sum_{i=1}^{n-1}P_{iL}^{(t)}$ stand for the sum of active power output all DERs and loads at specified time section *t*.

$$P_{SL}^{(t)}+\sum_{i=1}^{n-1}P_{iDER}^{(t)}-\sum_{i=1}^{n-1}P_{iL}^{(t)}-P_{loss}^{(t)}=0 \tag{3}$$

So we derive another key situation index, the confidential capacity namely $\tilde{P}_C$ of all DERs integrated, which has been defined as shown below.

$$\tilde{P}_C=\sum\tilde{P}_{iL}+\tilde{P}_{loss}-\tilde{P}_{SL} \tag{4}$$

Here, $\sum\tilde{P}_{iL}$ means the sum of each load node's average load active power within a specified time process. Similarly, $\tilde{P}_{loss}$ for average value of network active power loss, $\tilde{P}_{SL}$ for average value of power injection of slack node. This index refers to a particular value the intermittent power resource output may regularly fluctuates around or a certain range of deterministic value it may fall in with larger probability. It can be considered as a reliable estimate from the view of long time scale.

All these key indexes can be calculated based on dynamic power flow method for ADN and its results.

A DYNAMIC POWER FLOW APPROACH

Dynamic power flow method is essentially about operation trajectory searching and solving of the system under certain conditions, given a more accurate analysis of grid's status and characteristics under scene variations and uncertain conditions in continuous time.

The DPF method should be rapid in tracking random power fluctuations real-time and continuously adjust the output of the controllable equipment, then get the distribution of power flow the system reaches at new steady state, as well as the continuous power gradual changing process of state trajectory's movement. Thus, DPF method allocates possible random disturbances and requires a high real-time performance. A deterministic result can be derived by rapid iterative rather than by solving planning model or a probability of uncertain value.

It describes and reflects variations of the operation scenario. Different from that of transmission network, DPF method proposed in this paper for ADN with wind power and ESS integrated, aims at make full use of controllable ESS to improve the stability of the DER output. It provides power support for the network only when meeting its own constraint conditions such as capacity, charging and discharging rate.

ESS adjustment in accordance with stochastic output power of DER

A statistical index reflecting the long-term trend of wind power output characteristics is used. Exponential Moving Average (EMA) line represents the trend of the numerical change and movement. For any wind power turbine, the EMA indicator as shown below.

$$EMA^{(t)}=EMA^{(t-1)}+\sigma\cdot(P_{DG}^{(t)}-EMA^{(t-1)}) \tag{5}$$

Here, *t* means time stamp corresponding with values on EMA curves at this time. σ stands for smooth factor that varies from different time scales. $P_{DG}^{(t)}$ represents the current output power of wind power. Define two EMA lines with period of 10 seconds and 30 seconds. Thus the difference DIF of the two EMA lines corresponding to the same time is shown below.

$$DIF^{(t)}=EMA_{T-10}^{(t)}-EMA_{T-30}^{(t)} \tag{6}$$

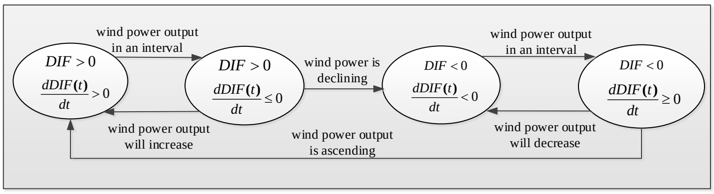

Fig.1 Indicators reflecting variations of wind power

The positive and negative of DIF value itself and the slope of its tangent form different combinations reflecting the variations of distributed wind power output as shown in Fig.1. Thus ESS adjust its output flexibly and continuously based on these indicators.

Dynamic power flow model for ADN

The active power output of ESS is a continuous variable changes which is about the time, adjusting itself by reasoning according to wind power fluctuations. Its model is shown below.

$$P_{ESS}(t)=P(t_o)+k\cdot t \tag{7}$$

Real time measurement information of load active and reactive power, wind active power can be taken into the node power imbalance equations expressed in (8).

$$\begin{cases}\Delta P_i=P_{iW}+P_{iESS}-P_{iL}-U_i\sum_{j\in i}U_j(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij})\\ \Delta Q_i=Q_{iW}-Q_{iL}-U_i\sum_{j\in i}U_j(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij})\end{cases} \tag{8}$$

Here, Q_{iW} stands for the reactive power output of PQV node considered asynchronous wind generator. It depends on node voltage, inherent parameters and active power.

Solution to the DPF model

The classical Newton-Raphson method is used to solve the DPF model expressed in equation (8). It is over too complicated to calculate the partial derivative of the voltage

amplitude of wind power integrated node. PQV node is considered as normal PQ node when solving the DPF model and neglect the relation between node voltage and reactive power of wind power. Thus the Jacobian matrix is identical to traditional Newton-Raphson method.
Considering voltage difference of adjacent nodes is small in distribution network, with very few grounding branches or even do not exist, therefore omit sinusoidal component in the Jacobian matrix and result to a simplified one.
Based on continuous output of DPF result, the key operation situation indexes can be calculated.

METHOD TO CALCULATE THE INDEXES

Total active power loss

Key situation indexes can be calculated utilizing the result of time continuous dynamic power flow, by which system operation state can be evaluated. A simplified solution to active power loss is developed.
According to the DPF result that the system moves to new steady point each time in a continuous time process, discrete sequence of each node's voltage and phase angle can be derived as well as the amount of changes compared to last balanced state.
Take node voltage for instance and the same for phase angle. Set $U_i^{(t)}=U_i^{(t-1)}-\Delta U$. If $U_i^{(t-1)}-\Delta U$ and $\theta_i^{(t-1)}-\Delta\theta$ are substituted into formula (1) as variables, then expand Taylor series of formula (1) at point $U_i^{(t-1)}$ and $\theta_i^{(t-1)}$, omitting two order and higher terms. This results to:

$$P_{loss}^{(t)}=P_{loss}^{(t-1)}-\left[\Delta A\ \ \Delta B\right]\left[\Delta\theta\ \ \Delta U/U\right]^{\mathrm{T}} \tag{9}$$

Here, $\Delta\theta$ and $\Delta U/U$ stand for change quantity of each node's voltage and phase angle compared to last balance state, instead of the corrections in power flow iteration equation. Power loss factor matrix $\boldsymbol{X}=\left[\Delta A\ \ \Delta B\right]$ can be achieved by calculating formula (10).

$$\begin{cases}\Delta A_{ii}=\dfrac{\partial P_{loss}}{\partial\theta_i}=-2U_i\sum\limits_{j\in i}U_jG_{ij}\,\mathbf{sin}\,\theta_{ij}\\ \Delta A_{ij}=\dfrac{\partial P_{loss}}{\partial\theta_j}=2U_j\sum\limits_{j=1}^{n}U_iG_{ij}\,\mathbf{sin}\,\theta_{ij}\\ \Delta B_{ii}=\dfrac{\partial P_{loss}}{\partial U_i}U_i=2U_i\sum\limits_{j\in i}U_jG_{ij}\,\mathbf{cos}\,\theta_{ij}\\ \Delta B_{ij}=\dfrac{\partial P_{loss}}{\partial U_j}U_j=2U_j\sum\limits_{i=1}^{n}U_iG_{ij}\,\mathbf{cos}\,\theta_{ij}\end{cases} \tag{10}$$

The angle between adjacent nodes in distribution network is very small. The value of ΔA in formula (10) is considered to be zero. Thus the network power loss of the next steady state can be achieved by formula (11), avoiding a large number of cumulative operations.

$$P_{loss}^{(t)}=P_{loss}^{(t-1)}-\Delta B\cdot\frac{\Delta U}{U} \tag{11}$$

Voltage deviation rate

According to DPF method generated result, it forms a time-varying vector about node voltage given below.

$$\boldsymbol{V}=[1-U]^{T} \tag{12}$$

According to the property of norm and Minkowski inequation we know that:

$$\sum_{i=1}^{n-1}(1-U_i)^2\le(\sum_{i=1}^{n-1}\left|1-U_i\right|)^2=(\left\|\boldsymbol{V}\right\|_1)^2 \tag{13}$$

That means $D_V=\dfrac{\left\|\boldsymbol{V}\right\|_2}{n-1}\le\dfrac{\left\|\boldsymbol{V}\right\|_1}{n-1}$. As for all node voltage of study case in this paper, none of them is larger than 1 *p.u.* Thus a simplified way to calculate the index D_V is given below with a large number of square and root computation avoided. If the index runs to get close to zero, it proclaims a good situation with voltage deviation rate low.

$$D_V\approx\left[\sum_{i=1}^{n-1}(1-U_i)\Big/n-1\right]\times100\% \tag{14}$$

Confidential capacity

With the DPF result reflecting changes of ADN in the specified continuous time period, variables located in the right side of the equal sign in formula (4) can thus be statistically calculated. And confidential capacity of all DERs in the network can also be figured out by substituting formula (15), (16) and (17) given below into formula (4).

$$\sum\tilde{P}_{iL}=\sum_{i=1}^{n-1}\frac{1}{T_p}\sum\Delta t_{ix}\cdot P_{ix} \tag{15}$$

$$\tilde{P}_{loss}=P_{loss}^{t_0}+\Delta\bar{P}_{loss} \tag{16}$$

$$\tilde{P}_{SL}=\int P_{SL}^{(t)}dt\Big/T \tag{17}$$

SCENARIO BASED ANALYSIS OF ADN OPERATION

Study case and scenario deployment

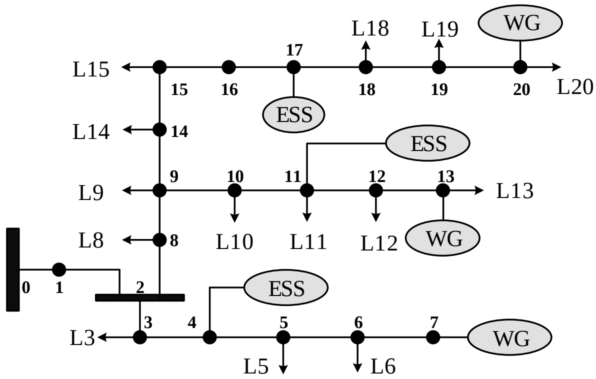

Fig. 2 A distribution network case with up to 20 nodes

Take a distribution network shown in figure 2 as study case. ESS for energy storage system and WG for wind power. Stochastic output power of wind power and loads vary from each other. Nominal parameter of each kind of DER is shown in Tab.1. The active power output of the wind power can be calculated according to the public meteorological data utilizing relevant classical formula and math model.

Tab. 1 Configuration of distributed WG and ESS

Equipment type	WG	ESS
Nominal power/capacity	700(kWp)	450(kWh)

Regardless of grid fault, we analyse its operation situation in a scenario that WG and load nodes stochastically and independently fluctuates in continuous 5 minutes based on DPF result of this study case.

Operation analysis

Overall active power loss variations of ADN within specified time period is shown in Fig.4. While affecting node's instantaneous voltage, DERs provide certain active power support on grid and eliminate transmission paths. As shown in Fig.3, when at 50s WG output and ESS output increase, P_{loss} decreases. After 150s, DER output increases and then decreases. P_{loss} index shows the opposite trend.

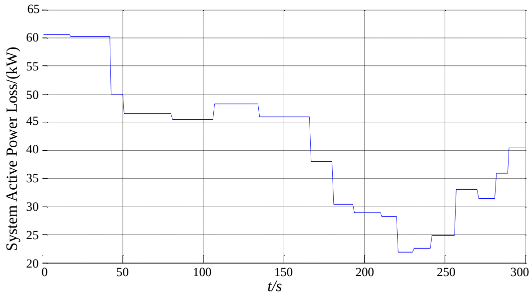

Fig. 3 Active power loss variations of the network

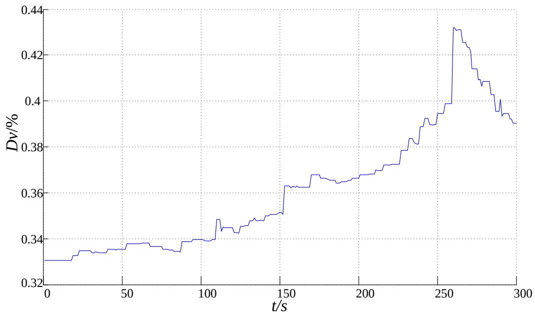

Fig. 4 Key index of voltage deviation rate variations

Fig. 4 shows the variations of voltage deviation rate as one of the key indexes of situation without compensation or voltage regulation. The fluctuations are irregular. In the case network, nodes at the end of branches which easily be affected by asynchronous wind generator may inevitably operates at a low voltage level especially when WG output increases. This contributes to the variations of desired index. Segment the curves shown in Fig.3 and 4 with a short time scale of 10 seconds. In each segment, initial and final value, maximum and minimum, fluctuation amplitude, slope of the tangent and information about external injections are combined to predict future trends in short terms. As for the study case in pre-designed scenario, P_{loss} will next gradually move into a stable interval with smaller fluctuations while the index of voltage deviation rate continues to decrease but with a slower speed.

With the same study case, another groups of WG and load dynamic data are chosen as different scenarios to calculate the grid's confidential capacity situation index.

Tab. 2 The confidential capacity in various scenarios

Scenario No.	1	2	3	4	5
Confidential Capacity(kW)	393	409	358	377	426

It can be concluded from Tab.2 that different scenarios result to various outputs. Statistical analysis based on numerous scenarios can achieve a more accurate result. This index also represents reliability and sufficiency for a secure power supply. It will be of help for planning and operation to accurately acquire the supporting performance of intermittent DER for distribution grid.

CONCLUSION

Key operation situation index are established and proposed a dynamic power flow approach to calculate the indexes and evaluate operation state while reflecting its trends. Effectiveness of the proposed method is verified through selected study case and pre-established scenario. The value of operation situation indexes and evaluation of system state have been given. Besides, potential trend or direction the system may move towards in short terms has also been analysed and revealed.

With the result the proposed method provides, necessary control and management measures can be taken to secure an optimal operation. So this will lead to a more reliable power grid and helps operation to achieve higher efficiency.

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