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Modeling of intelligent distribution network self-healing control state transition based on FSM

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Abstract: In order to realize effective prevention from faults, cut-off the fault quickly and power supply recovery from power loss load in intelligent distribution network, this paper proposed a state transition model of self-healing control for intelligent distribution network based on Finite State Machine (FSM). We divided the running states into normal state and fault state, added finite variables to FSM. determined the operation state transition control schemes of intelligent distribution network self-healing control. Considering distributed generation(DG), we established the state transition model of intelligent distribution network self-healing control system on Matlab/Stateflow platform and applied to simulation example. The results show that the proposed state transition scheme is feasible and effective.

1. Introduction

Distribution network directly faces power users, which is the key link to ensure the quality of power supply, improve the operation efficiency of power grid and innovate user services[1]. As the "immune system" of intelligent distribution network, self-healing control is an important link to ensure the high reliability operation of intelligent distribution network[2]. With the annual increasing the penetration rate of DG and the complexity of the power grid topology, the safe and stable operation of the distribution network has brought hidden dangers[3].

Self-healing control has become a research hotspot in distribution network management and control. Bin Li restored important load power supply by ensuring DG joint operation, and reserved 30% capacity of controllable DG to ensure the feasibility of operation[4]. Xinyue Chen conducted discrete probability modeling for photovoltaic power generation, which took the power fluctuation into better consideration and improved the feasibility of restore plan[5]. Mendoza J E believe that there is a demand side response mechanism, and load can be cut off according to a certain priority relationship to preserve the reliability of important loads[6].

Combined with the development status of self-healing control of intelligent distribution network, this paper established a state transition model based on FSM. Considering the output of DG, the control method of running state transition was determined. The system state transition model was built on Matlab/Stateflow platform and the results were verified by example simulation.

2. Finite State Machine

FSM is a basic formalization technique that can be used in all phases of the system life, from system specification to system design[7]. FSM is generally defined as a 5-tuple: $FSM=(\Sigma, Q, \delta, q_0, Q_m)$. Where Σ is the finite event set. Q is the finite state set. δ is a conversion function: $Q \times \Sigma \rightarrow Q$, namely $\delta(q,x) \rightarrow q'$,



when FSM on the state Q , reading character 'x' arrive the state Q' . q_0 is the initial state. Q_m is received state or set of terminated states.

A FSM contains a finite number of states, but it can only be in one of them at any given moment. State change is driven by events, the traditional FSM has state explosion problem, making it unsuitable for some practical applications. On the other hand, the number of states required can be greatly reduced by using an integer variable to describe the contents of the buffer. In addition, when the buffer changes, variables can be modified without remodifying the system[8]. For this purpose, both FSM and the set of variables are used in the modeling, and their definitions are similar to extending FSM.

Introduce variables into the FSM, assuming that $p \in P$ is the set of variables, where p is a vector space, we introduced the protection $g \in G$ based on the variable p , as shown in figure 1, transformation function δ can be defined function from $\Sigma \times Q \times G \times P$ to $Q \times P$.

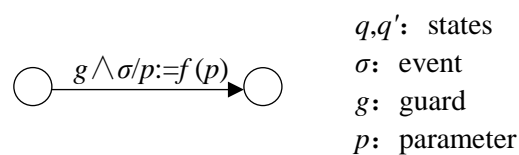


Figure 1 Conversion diagram of FSM

When FSM is on the state q and the guard g is true and the event σ occurs, it reaches state q' and the value of variable is updated to $f(p)$. FSM introduced variable is a 7-tuple: $FSM = (\Sigma, Q, \delta, P, G, (q_0, p_0), Q_m)$, where p_0 is the initial value of variables when the state machine is on the initial state q_0 .

3. Operation state division of self-healing control

In order to realize that intelligent distribution network has self-healing ability, which is mainly reflected in three aspects: prevention in advance, treatment in process and recovery after the event[9]. The operation state of intelligent distribution network is divided into five states.

3.1. State division

(1) Optimization state: the distribution network operates stably, safely and reliably with low loss and low operation cost at the current load level.

(2) Safety state: it meets the load constraint and operation constraint conditions. There is no isolated power supply and no failure occurs.

(3) Abnormal state: the duration of overload is allowed, without serious low/over voltage or abnormal operation of power equipment.

(4) Restoration state: the system can still meet the operation constraints, but there is still a loss of power load or power supply island.

(5) Emergency state: the distribution network has a failure, or a serious low/over voltage, or a serious overload.

3.2. Control method

(1) Emergency control: the distribution network is in emergency state, there is a failure, it can be restored to normal state after automatic reclosing of the circuit. For permanent failure, it is necessary to take control measures such as load cutting and active disassembly to make the system transition to the recovery state, abnormal state or normal state.

(2) Restoration control: the distribution network is in restoration state. The system parameters can meet the operation constraints, but there is still a loss of power load or an isolated island of power supply, and it does not reach the normal state. The reasonable power supply path should be selected to restore the load power supply and make the distribution network transition to normal or abnormal state.

(3) Preventive control: the distribution network is in abnormal state, with over-load but the duration is in the allowable range, or there is no serious over-voltage or low voltage. It is necessary to take control measures to eliminate overload and voltage over limit, to make the transition to safe state.

(4) Optimal control: the distributed network is in safe state. By changing the power supply path and adjusting the reactive power compensation equipment, the loss of the network can be reduced and the operation cost can be reduced, so that the distribution network can be transferred to the optimal state.

3.3. Self-healing control state transition model

The instantaneous maximum load at node i is recorded as P_L , P_i is the maximum power that the distribution network can provide to this node, P_{DG} is the power that each DG connected at node i can provide, and n is the number of DG.

The specific running state is defined as follows:

- (1) Optimal state O: $0.9P_i \geq P_L$.
- (2) Normal state N: $P_i > P_L \geq 0.9P_i$.
- (3) Normal state ND: $nP_{DG} + P_i \geq P_L$.
- (4) Abnormal state A: $P_i \leq P_L < 1.1P_i$.
- (5) Restore state R: $1.1P_i < P_L$.
- (6) Urgency state U: $nP_{DG} + 1.1P_i < P_L$.

According to the division of the operation state of the self-healing control of the smart distribution network, the state transition model of the self-healing control based on FSM was established in the Stateflow platform, as shown in Figure.2.

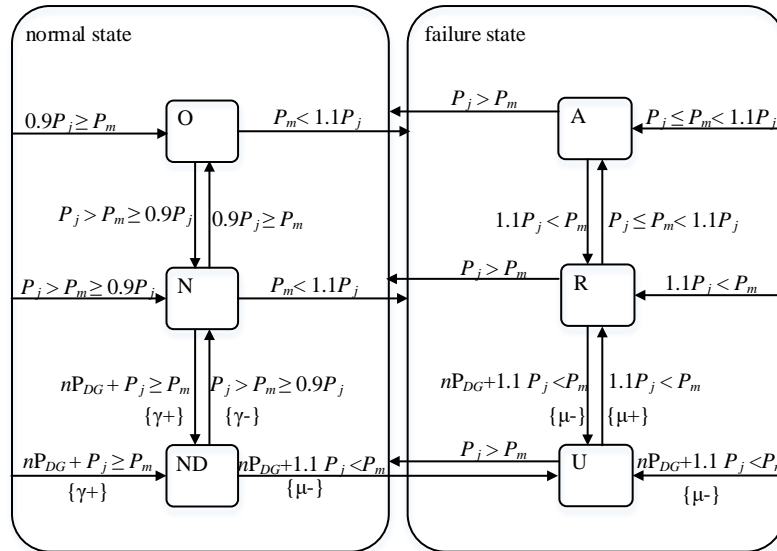


Figure 2 State transition model of self-healing control based on FSM

When DG or load changes, time set Σ consists of the following events:

- (1) α^- : Node i is in the fault of the distribution network and cannot supply power to node i ;
- (2) α^+ : The distribution network fault at node i is eliminated and power supply to node i is restored;
- (3) β^- : The load $P_{i,L}$ at node i are reduced;
- (4) β^+ : The load $P_{i,L}$ at node i are increased;
- (5) γ^- : DG is removed at node i , that is, $P_{DG}=0$;
- (6) γ^+ : DG accessed at node i , that is, $P_{DG}=0$;
- (7) μ^- : The circuit breaker at node i is disconnected, that is, $P_i=0$;
- (8) μ^+ : The circuit breaker at node i is closed.

The executable event:

- (1) μ^- : The circuit breaker at node i is disconnected, that is, $P_i=0$;
- (2) μ^+ : The circuit breaker at node i is closed.

The introduced variable:

- (1) P_{DG} : the power that can be provided by each DG connected at the i -th node;
- (2) n : The number of DG connected at node i .

Since the load P_L at node i of the distribution network is random and intermittent, which will change with time or emergencies. While P_j is the stable power by the distribution network. Introducing variable n into FSM, when a fault occurs, by controlling the value of n , adopting the way of transfer to supply power to fault area load by DG, without having to manually restore lost electricity or automatic reclosing made fault area[10], shortens the fault location, fault handling and fault recovery time, reduce the impact of the multiple overlapping on the system itself and don't need a lot of condition number, effectively using FSM model display node i dynamic failure load and the healing process.

4. Example simulation and analysis

The operation state of the self-healing control system of smart distribution network is related to the change of node load and the access and removal of DG. The FSM modeling method based on executable events and controllable variables is adopted. The required working conditions are as follows:

- (1) The fixed output power of the distribution network remains unchanged, and the main control methods are to connect DG and cut off part of the load to achieve self-healing control.
- (2) Load demand changes with time, and the change is similar to the step function.
- (3) The simulation process characterizes the system state transition according to the difference between the output power and the power required by the load.

The load conditions obtained are shown in Figure 3.

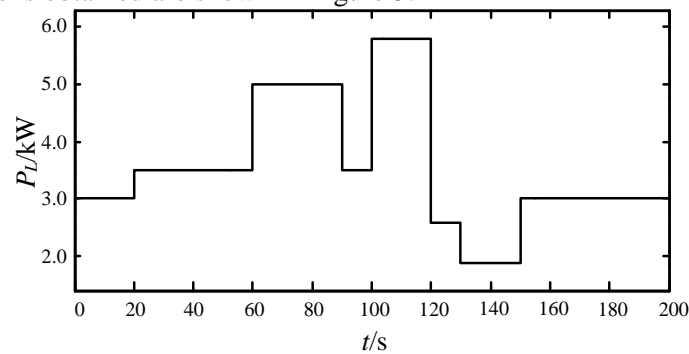


Figure 3 Load operating mode curve

The natural output power of the distribution network $P_L = 3.3\text{kw}$. There are 3 DG standby units at the node, each output power $P_L = 0.6\text{kw}$. The output power curve is shown in figure 4. Selected above example simulation operating mode, running state using STATEFLOW simulation output is O (Optimal state), N (Normal state), ND (DG output when security status), A (abnormal state), R (Restore state), U (Urgency state), in the above condition according to the demand side load changes in state conversion to each other, as shown in figure 5 for the state machine output. Figure 6 shows the final output of the whole self-healing control system.

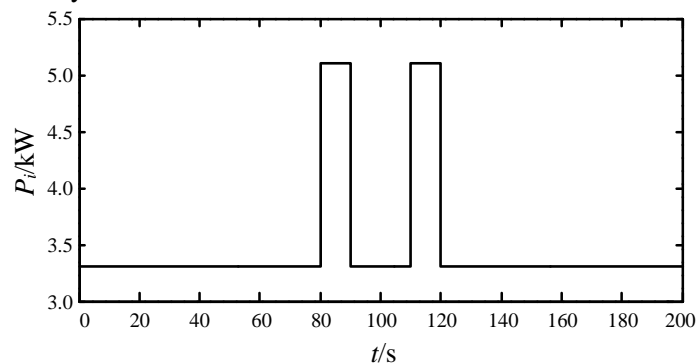


Figure 4 Output power curve of distribution network

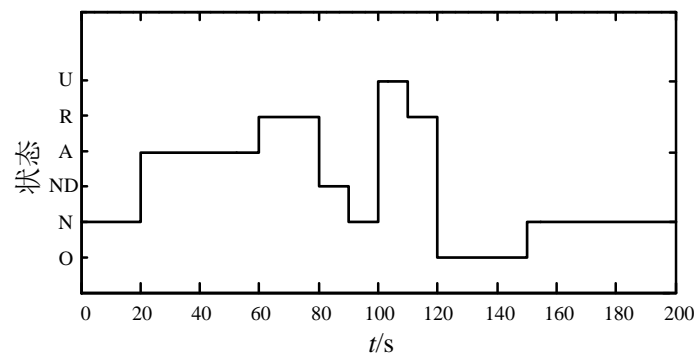


Figure 5 FSM output

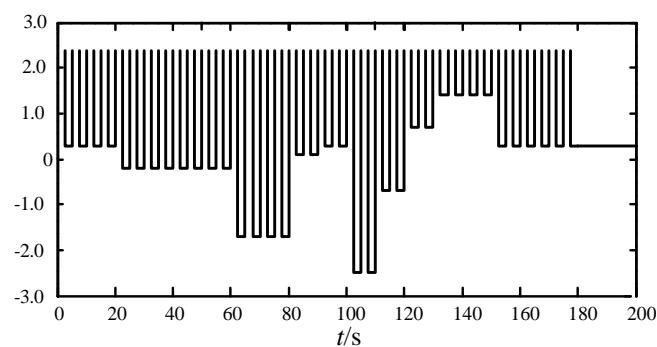


Figure 6 Output waveform

According to the given example, when the input power of the distribution network P_i is equal to 3.3kW, according to the output waveform of system output through the difference between P_i and P_L , it is completely consistent with the output of system state under the same working condition, which verifies the feasibility of the transformation model of smart distribution network self-healing control system based on FSM.

5. Conclusion

(1) For the self-healing control system of smart power distribution network, the state transition control strategy and modeling method based on FSM are proposed, and the controllable variables PDG and n are introduced into the FSM model, which greatly reduces the number of states, economic cost and system loss.

(2) The modeling method based on FSM is consistent with the characteristics of closed loop design and open loop operation of intelligent distribution network, so as to realize the coordinated power supply to users by distribution network and DG and give full play to the role of DG.

(3) The control model can trigger events, judge state migration conditions and perform migration actions, so that the self-healing control system can make normal transition between various operating states. The output waveform of the simulation example is completely consistent with the output of the state machine.

Acknowledgments

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