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A Fast Online Load Shedding Method for Mitigating FIDVR Based On Novel Stability Index

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Abstract— This paper presents an online fast load shedding method for mitigating Fault-Induce Delayed Voltage Recovery (FIDVR), using a new stability index. After fault clearing in a power system, the voltage may remain in lower levels for some seconds, which may result in voltage collapse in severe cases. In this paper, a new index, to identify instability, is presented, based on induction motor model. Instead of using voltage amplitude as a stability indicator, the proposed method applies a centralized scheme, using new the index. The new load shedding algorithm is applied to a practical test system in order to verify the proposed stability index and load shedding methodology. Simulations show the effectiveness of proposed method in decreasing the voltage recovery time.

Keywords: FIDVR; load shedding; stability index; voltage stability

I. INTRODUCTION

Recently, the Fault-Induced Delay Voltage Recovery (FIDVR) has attracted the attentions as a significant issue in power systems [1]. The FIDVR is a phenomenon, whereby system voltage remains at significantly low levels, after a fault clearing in transmission, subtransmission or even distribution systems, for some seconds [2]. In such an incident, high load currents and large reactive power demands caused the delays up to tens of seconds for voltage to recover after a fault clearing.

Studies show that FIDVR phenomenon usually happens in the systems including induction motors with constant torque load characteristic. Such type loads, may stall in reaction to the sustained low voltage level, which results induction motors to draw excessive reactive power from the power grid [3]–[6]. In practice, severe FIDVR event could lead to fast voltage collapse.

The studies on controlling FIDVR are classified in two main groups. The first group includes supply side solutions, while the second group is about demand side solutions. The most popular supply side solutions are based on using FACTs devices. [7]–[10] present solutions using SVC and [11] presents a solution using STATCOM to provide reactive power. While, the solutions based on using FACTs are very expensive, they are not fully effective in preventing fast voltage collapse [1].

Demand side solutions protect the system by disconnecting loads under low voltage conditions. The demand side solutions are effective and economic to undertake FIDVR. [12] proposed a method for undervoltage load shedding, based on voltage recovery rate and predicted time to recover. A MVA-Volt index was proposed for steady-state screening of buses to identify FIDVR in [13]. [14] Presents an under-voltage protection method using 78% of the motor rated voltage as the threshold for stalling protection. [15] develops a novel online fast load shedding strategy aimed at shedding the most effective load to mitigate FIDVR using the induction motor kinetic energy deviation. Support Vector Machine (SVM) classifier is used to develop a technique that can predict the transient stability status after a fault, using the post-fault voltage variation measured at the high voltage generation buses of a multi-machine power system in [16].

In this paper, a novel stability indicator, based on induction motor model, is proposed. This index indicates the motor condition. Based on the newly proposed index, a novel load shedding scheme is proposed. The effectiveness and accuracy of the new index and load shedding scheme is verified by applying the approach to a practical system.

II. NEW STABILITY INDEX

The new index is an indicator which shows the induction motor condition. In other words, the mentioned index is an indicator to show the distance between motors operating point and stalling point. Critical slip, $S_c$, does not change with voltage magnitude changes. The motor stalls, if the mechanical torque becomes greater than the electrical value. Fig. 1 shows the motor active power and reactive power characteristics versus slip and voltage magnitude, respectively. It may be shown that the stable operating region is the left side of P-s characteristic and the peak of curve is critical slip point. $Q_T$, $Q_m$ and $Q_l$ are the total reactive power of induction motor,
magnetizing reactive power and stator reactive power, respectively.

For understanding the induction motor characteristic, an appropriate model is required. Induction motor is represented using a traditional steady state model [15]. Fig. 2 shows the traditional and simplified versions of induction motor model.

The stator resistance and reactance, respectively. The rotor resistance and reactance and $X_m$ is magnetizing reactance of induction motor. As $R_s$ is small and $X_m$ is much greater than $X_s$, the model can be simplified as Fig. 2. In the simplified form, the $X_{eq}=X_s+X_r$ and $R_{eq}=R_r$ are the equivalent reactance and resistance, respectively. In the simplified model, the voltage and current equations are as follows:

\[ I^2 = \frac{V^2}{X_{eq}^2 + \left(\frac{R_{eq}}{s}\right)^2} \]  
\[ P_I = I^2 \left(\frac{R_{eq}}{s}\right) \]  
\[ Q_I = I^2 X_{eq} \]  
\[ Q_w = \frac{V^2}{X_m} \]  
\[ Q_{TL} = Q_m + Q_I \]  

$Q_{TL}$, $Q_m$ and $Q_I$ are the total reactive power of induction motor, magnetizing reactive power and stator reactive power, respectively. The critical slip is calculated as follows [15]

\[ S_c = \frac{R_m}{X_{eq}} \]  

Fig 1 shows the $Q_{TL}$, $Q_I$ and $Q_w$ as a function of voltage magnitude. As seen in Fig. 1, the induction motor consumes a very large amount of reactive power in its stalling point. Stalled motors, in the voltage recovery condition, reduce the recovery sleep. Therefore, may result in voltage collapse.

The proportion of electrical torque to critical torque, which occurs at $S_c$, shows the condition of induction motor. Hence, it is a proper index as a stability indicator of asynchronous machine. The problem with this index is that the required data are not available in relays location. The index should be estimated using available data. The procedure is as follows [15]:

\[ \frac{T_e}{T_c} = \frac{2}{S - \frac{S_c}{S}} \]  

By replacing (2), (4) and (6) into (7), it is rewritten as follows:

\[ \frac{T_e}{P_I} = \frac{Q_T}{Q_I} = \text{Index} \]  

Whenever the index is greater than 1, the motor is in stable condition which is the left side of P-s characteristic. When the index becomes equal to 1, the motors reach critical stall point. Thus, instead of using voltage amplitude as an indicator, which is not a proper index, a new index is introduced which shows the instability condition, independent of voltage level, operating condition, and etc. The problem with (8) is that the value of $Q_I$ is not directly available. The value of $Q_{TL}$ and $P_I$ are directly available, from the measurements. Therefore, $R_l$ should be calculated, using the available parameters.

Various calculations on different motors show that the value of $Q_I/\theta_{TL}$ is a function of voltage magnitude. Fig. 3 shows the mentioned function for a simple induction motor. The motor data is available in appendix I.

As shown in Fig. 3, the derived curve may be fit to a line, which is depicted as dashed line in Fig. 3. Further simulations will show that the fitting effect on the results is negligible.

Therefore, the indicator can be rewritten as follows:

\[ \text{Index} = \frac{Q_{TL} \left( k - m V \right)}{P_I} \]  

where (9) is the final equation for calculating the index value. All the parameters, used in (9), are available.
A new load shedding scheme is defined based on the new stability index. The purpose of the load shedding method is to inhibit voltage collapse through preventing FIDVR. The new scheme is using local measurements. Since the load shedding decision is made locally, based on the local measured quantities, no communication link is required for implementation of this method.

In this scheme, the relays are distributed in all of the network buses. The relays require voltage magnitude, active and reactive power for their process, which are locally available. In this scheme, the voltage stability index is calculated in real-time, and when the index value reaches a pre-defined value, the load shedding relay operates.

In the simulations, the threshold value is assumed to be equal to 2. When the index falls below the threshold and remains smaller than the threshold for 10 cycles, the relays operate and disconnects the load from network. The delay time is considered in order to improve the security of scheme. The delay causes the scheme to be more secure and to shed fewer amounts of loads. In some conditions, the relays in adjacent buses, reach the shedding condition earlier, so the network may recover and become stable. The considered delay causes the load shedding relays to wait for recovery and also, not to shed loads in transient conditions.

IV. SIMULATION RESULTS AND ANALYSIS

Proficiency of the proposed stability indicator is tested through dynamic simulation of a part of the Iran national grid: high voltage network of the Khorasan province. Fig. 4 shows the single line diagram of the Khorasan province. The data for the Khorasan province are obtained from [17]-[19]. The Khorasan province network includes 75 high voltage 132-kV and 400-kV buses. The main power plants are located in the north of this network and long 400-kV and 132-kV transmission lines transfer the power to far distances in this network. Therefore, Khorasan province network is vulnerable to voltage instabilities as a result of some contingencies and is suitable for performance investigation of the new stability indicator and load shedding algorithm, which is based on the new stability index.

In order to test the new stability index efficiency and load shedding method two cases are explored. In both cases, a fault is simulated in midpoint of 400kV line which connects the Toos bus to Torbatjam. The line length is 195(km) and it delivers 110(MW) from Toos to Torbatjam. In the defined event, the line is disconnected for fault clearing. The fault occurs in the 20th cycle and the line is disconnected after 4 cycles. Fig. 5 shows the voltage of some of buses. The figure depicts that the voltage of some buses remain in lower levels, which is the result of induction motors stalling. In this case, due to FIDVR phenomenon, some of the induction motors are stalled. Referring to Fig. 1, when motor stalls, it is under the locked-rotor condition which consumes five to six times the steady-state motor current and thus demands a largely increased reactive power. Drawing a large amount of reactive power, not only decreases the speed of voltage recovery, but also, it may cause voltage collapse as it happens in this test case. Fig. 6 shows one of the stalled motors reactive power. As Fig. 6 depicts, the reactive power of stalling condition is almost 8 times of normal condition.

A. Performance of new stability index

Fig. 7 shows the load curve of a sample motor in Khorasan province network. Referring to load curve of the mentioned
induction motor, the critical slip is equal to 0.13. Critical slip is insensitive to the amplitude of voltage. As the motor reaches the critical slip, it stalls and the motor operates in the right side of curve which is unstable condition.

Fig. 8 depicts the slip curve of induction motor for 200 cycles. The motor reaches its unstable condition in the 63rd cycle.

Fig. 9 is shows the stability index for mentioned motor. As defined in previous sections, the index value should decrease to 1, as the motor moves to unstable condition. As the motor stalls, the stability index value should be equal to 1. As Fig. 9 shows, the instability index value is almost equal to 1 in 63rd cycle.

As Fig. 8 and Fig. 9 depict, the instability index represent the motor instability, accurately. It shows that when the instability occurs in the 63rd cycle, the index is exactly equal to 1. Therefore, using the proposed index, it is possible to predict the instability, when the index becomes close to 1.

B. **Performance of new load shedding method**

Fig. 10 shows the index values of some loads. The most unstable buses are selected to be depicting in Fig. 10. Simulation results show that five buses are going to reach the unstable condition. As mentioned in previous parts, as the index values falls below the threshold value, and remain 10 cycles in this condition, the load shedding relay operates. Simulations show that, shedding two loads, which depict in red color in Fig. 10, are adequate for tackling instability. In other words, as the loads reach to shedding condition, the load disconnected from network, and after disconnecting first and second loads, the index values ascend to higher value, more than threshold. The total load which is shed is almost 23 (MW). Two buses, which their loads are selected to be shed, are SALEHABAD and SOLAT. The SALEHABAD load shedding relay operate in 51st cycle and SOLAT relay operates in 59th cycle. The next relay which was expected to operate, did not operate because of index ascending. In other word, load shedding in previous buses, cause the index value to return to higher levels.

Fig. 10 shows the voltage of some buses after load shedding. As Fig. 10 depicts, the voltages are recovered and none of the motors reaches stalling condition. The new load shedding scheme shed almost 2.7% of total load, which shows the efficiency of proposed algorithm. The load shedding prevents system instability and also, reduces the fault induced voltage recovery time. The time needed for recovery of voltage of all buses, after fault clearing, is about 1.3(s).
V. DISCUSSION

This work presents a new load shedding scheme for tackling FIDVR phenomenon. This new algorithm is based on a new stability indicator. The proposed technique has some significant advantages. The following important features should be considered about this algorithm:

- The new stability index is fast and requires voltage, active and reactive power values, which are available in all of the buses.
- Since the load shedding decision is made locally based on the local measured quantities, no communication link is required for implementation of these methods.
- A delay is considered in order to reduce amount of load to be shed and increase security level of the algorithm.
- The new indicator is defined in a way that the stable and unstable condition border is constant, unlike voltage amplitude which is variable for each bus, in any condition.
- The accuracy of new index was verified in a practical network.
- Performance of the proposed load shedding method is tested through dynamic simulation of a part of the Iran national grid: high voltage network of the Khorasan province.

VI. CONCLUSION

In this paper a fast online load shedding method is introduced for mitigating FIDVR, based on a novel stability index. The index value in normal operating mode is greater than 1. The instability occurs when the value of index decreases to 1. One of the main advantages of proposed index is that it is independent of operating condition and the instability threshold is constant, unlike voltage amplitude. A new load shedding scheme is introduced for tackling FIDVR based on the new index. New load shedding algorithm operates locally. Simulations depict the accuracy of proposed stability index and performance of presented load shedding technique. The presented load shedding method is applicable to any power system, since it uses local measured values for making load shedding decision.

APPENDIX I

The modeled motor data is as follows:

| TABLE I. PARAMETERS OF THE APPLIED INDUCTION MOTOR |
|-----------------|-------------|
| Stator Resistance (ohm) | 39.0760 |
| Stator leakage reactance (ohm) | 117.2280 |
| Magnetizing reactance (ohm) | 3855.5000 |
| Rotor resistance (ohm) | 39.0760 |
| Rotor leakage reactance (ohm) | 195.3800 |

REFERENCES


