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A study on critical clearing time (CCT) of micro-grids under fault conditions

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ABSTRACT

The increasing penetration of distributed generations (DGs) in the electrical system is causing a new system transient stability problem since most of DGs are characterized by low inertias and poor inherent damping. Measures such as application of storage unit and wind turbine crowbar protection have been proposed to enhance the transient performance of micro-grid. However, the increase in the number of micro-grid components also leads to changes in system critical clearing time (CCT) under fault conditions. This paper investigates the various features affecting the CCT of a micro-grid in an islanded mode. The result shows the traditional equation cannot be used to calculate the CCT and the wind turbine disconnection is the main reason causing the micro-grid collapse. The DG penetration level and the wind turbine crowbar protection insertion time can have significant impacts on the CCT value, and the CCT can be substantially increased by utilizing battery storage in the micro-grid.

1. Introduction

Distributed generations are characterized by low inertias, high reactance, short time constant and poor inherent damping [1]. Consequently, the dynamic performance of the whole system may be adversely affected since DGs do not have the capability to regulate the system stability [2], especially when the micro-grid is operated in islanding mode, which incur more difficult and expensive energy supplies [3].

Many researchers have analyzed the micro-grid stability and have suggested methods to improve the dynamic performance of the system. Reference [4] presented the stability evaluation of a micro-grid and the future interconnection with an AC system. An investigation of a continuous energy mix strategy was discussed by adding an additional DC power line to the local power distribution system [5]. An approach based on matrix perturbation for the co-ordinated optimization of droop coefficients in the micro-grid was proposed to ensure the stability of the system [6]. A method for improving the distributed charge/discharge control of energy storage was presented in Ref. [7]. A control scheme to minimize the islanding detection delays and random disturbances associated with mode transfer was introduced in Ref. [8]. However, this enhancement is achieved by installing the voltage source converter whilst the characteristic of this source is not specified; additionally, it cannot be utilized for monitoring the transient behavior of the wind turbine. The authors of reference [9] suggest that an appropriate choice of DG's location will help to improve the stability of the system; however, only the basic model of the doubly fed induction generator (DFIG) based wind turbine is used without considering voltage ride-through requirements, and the results are not validated through experimental work. The micro-grid performance with both DFIG based wind turbine and energy storage is investigated in Ref. [10]. Although the authors discuss a detailed modeling of the micro-grid in an isolated mode, the transient analysis is actually performed in the grid-connected mode.

With the increasing penetration of wind energy into the power system, the voltage ride-through capability of the DFIG has received more and more attention [11]. The DFIG experiences overcurrent which also leads to an increase of DC voltage on the converter side during the disturbance [12]. To protect the wind turbine, the DFIG has to be isolated from the grid in a certain time; however, the loss of the DG generation may cause the collapse of the system voltage and the wind turbine is unable to re-synchronize into the micro-grid. So the disturbance should be cleared before the wind turbine protection operates to cut-off the generator and thus, the critical clearing time (CCT) for a micro-grid is determined by the

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wind turbine protection operation time.

Some previous researches have investigated the dynamic behavior of the wind turbine. Ref. [13] reviews many technologies used to control and to improve the quality of the power generated from wind turbine system, but the authors also point out that the application of wind energy still confronts a wide range of new challenges in design, development, manufacturing, installation, maintenance and operation. Reference [14] shows that the application of crowbar protection can improve the wind turbine performance during the fault. Alaboudy and Zeineldin [15] proposed a micro-grid with a mixture of synchronous generators and inverter-interfaced DG and showed that this has a better transient stability performance and its critical clearing time is larger than that of the micro-grid with 100% synchronous DG. Many other researchers [16–18] have discussed the wind turbine fault transients with different control strategies and protection, but they have not analyzed the CCT for the micro-grid. Reference [19] presents a method to evaluate the CCT of micro-grid by comparing the unstable operating speed of the wind turbine and the maximum operating speed of the generator after the fault. However, the wind turbine model used here can only be operated in grid-connected mode and also, the crowbar protection and the low voltage ride-through (LVRT) requirement are not considered in this research. Another calculation method is applied in Ref. [20] by using an improved steady-state equivalent circuit method, and the only factor used to discuss the CCT in this paper is the speed of the distributed induction generator, but the LVRT requirement and battery storage are still missing.

Battery storage is one of the most efficient methods to enhance the micro-grid transient performance [21–23]. The energy is stored in the form of electrochemical energy, in a set of multiple cells, connected in series or in parallel or both, in order to obtain the desired voltage and capacity [24]. Though renewable energy sources (RES) are inexhaustible in quantity, they are characterized with fluctuating power output as commonly observed in wind and solar power systems. Hence, the energy storage can act as a regulator that manages the fluctuations of electricity from renewable energy resources and alleviates both long-term and short-term system transients [25–27]. The application of the battery storage in the micro-grid has also an advantage of changing the fault current to a desired level, thereby allowing protection to operate in a traditional way [28]. So the impact of the battery storage on micro-grid transient is discussed in this paper together with the DG penetration level and wind turbine crow-bar protection.

In this work, the CCT for micro-grid is investigated and the simulation is carried out to determine the CCT for different micro-grid configurations in islanded mode. Critical factors which impact the micro-grid transient performance are examined and the CCT values are obtained.

2. Critical clearing time in micro-grid

The Critical Clearing Time (CCT) is the maximum time interval by which the fault must be cleared in order to preserve the system stability. This CCT is essential to evaluate the system performance but it is affected by many factors. As such, little research has been carried out to investigate the CCT in micro-grids.

In traditional networks, the CCT is defined as:

$$t_{cr} = \sqrt{\frac{4H}{2\pi f}(\delta_{cr} - \delta_0)} \tag{1}$$

where:

H is the inertia constant of the synchronous generator
f is the rated frequency of the system
δ_{cr} is the critical clearing angle
δ_0 is the initial power angle

The CCT is defined by the characteristic of synchronous generator (SG) in traditional network. However, for the micro-grid with multiple DGs, the inertia of DGs is small. Also, the voltage sag appearing during the fault may cause a power reversal of some DGs, which means, the power may flow into the converter from the grid side to avoid the overcurrent and to maintain the DC voltage constant. The grid voltage is affected and it may be difficult to recover when the fault duration is long. In this situation, the grid voltage is under the lower limit even through the SG is stable. Under the worst situation, the protection may cut the DG off from the system when it works in low voltage for a certain time. The system stability is strongly impaired and this may be the main reason for the micro-grid instability rather than the SG characteristic.

3. Fault protection of DFIG wind turbine

For DFIG based wind turbine, crowbar is the most commonly used protection method against the large short circuit current caused by the sudden drop of grid voltage.

Fig. 1 shows the topology of a typical crowbar protection. The crowbar will be quickly inserted into the rotor side in order to limit the short circuit current and prevent the system from being damaged [30]. However, if the fault duration is large and the crowbar is connected for a long time, the problem of reactive power absorption arises which will delay the recovery of grid voltage [11].

4. Voltage ride-through of wind turbine

1. High voltage ride-through

The micro-grid may suffer overvoltage when a disturbance occurs. The wind turbine should keep operating to maintain the system stability. Therefore, the high voltage ride-through (HVRT) requirement must be considered when studying micro-grid transients. As indicated in Fig. 2(a), the grid codes in Australia [31] ascertain the wind turbine to withstand a 1.3pu overvoltage for about 60 ms.

The DG integration and decrease in system load demand may lead to a power reversal in the grid-side converter, which means the power may flow from the micro-grid to the DC side of wind turbine. This may lead to an increase of the DC voltage and decrease of the wind turbine output current. To protect the converter, the DC voltage should be reduced to its initial value and the current through the converter should also be limited as the IGBT is highly sensitive to the overcurrent [32].

2. Low voltage ride-through

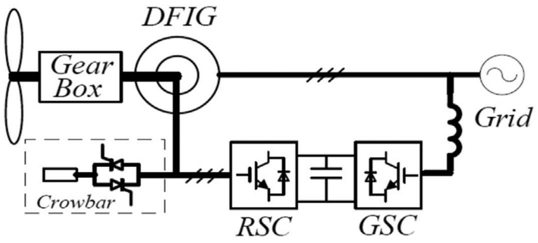

Fig. 1. The topology of a typical crowbar protection [19].