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Full Length Article

Analysis of doubly-fed induction machine operating at motoring mode subjected to voltage sag

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ABSTRACT

Variable Speed (VS) Pumped Storage Plants (PSP) equipped with large asynchronous (Doubly-Fed Induction) machines are emerging now in hydropower applications. Motoring mode of operation of Doubly-Fed Induction Machine (DFIM) is essential and techno-economical in this application due to: (1) its uniqueness in active power controllability, (2) bulk power handing capability with less rated power converters in rotor circuit, and (3) integrating Renewable Energy Sources (RES). This paper investigates the performance of two DFIMs at different power ratings (2.2 kW and 2 MW) under voltage sag with different attribute. The test results are analyzed in terms of the peaks in torque, speed, power taken and transient currents in rotor and stator circuits. During sag, stable region for DFIM operation along with speed and stator side reactive power input control is also illustrated. The negative effects of voltage sag are briefly discussed. MATLAB simulation is validated with experimentation. The various observations during simulation and experimental analysis are also supported by the theoretical explanations.

1. Introduction

The VS motor-system technology is most significantly used in various fluid-handling applications (fans, pumps and compressors) for adjustable flow and head [1]. The conveyors, lifts and centrifugal machine tools are other possible applications that are benefited by VS technology [1]. The power electronic converter as Variable Speed Drives (VSDs) coupled in series with three-phase AC motors (synchronous machine/mostly used squirrel-cage induction motor) have become a prominent and standard VS system that alleviates other practical technologies like hydraulic, mechanical gear-box and DC motors [1,2]. In induction or synchronous motor, the supply frequency is directly linked with speed of rotating magnetic field. Therefore, the two stage (AC-DC-AC) power electronic converters provide supply at variable frequency and voltage magnitude, hence the desired speed and torque are obtained [3–5].

With stern rule and regulation for environmental awareness worldwide, more attention has been paid to cheap and clean energy generation [6]. Therefore, in 2013 an astonishing expansion of 22.1% of total energy generation was achieved by RES throughout world [7]. Continuous growth in RES generation opportunities and challenges, both today and tomorrow, can mitigate greenhouse gas emission from conventional generation [8–10]. However, uncertainty and volatility is always associated with RES, hence an unpredictable power production can result to high power fluctuations in interconnected grid system that can even lead to failure of the entire system [11]. In such a scenarios, energy storage devices are desirable at different locations, so that surplus power in the grid can be stored and used during low-power or no-power generation periods. The available energy storage is in the form of batteries [12], superconducting magnet energy storage, flywheel energy storage, regenerative fuel cell storage, compressed air energy storage and PSP [13,14]. However, large capacity (both quantity and duration) of energy storage is available with PSP, which is economical and commercially viable. Subsequently, PSP provides quick response for change in grid frequency and unscheduled change in system loading [14]. PSP can store excess available energy in the form of gravitational potential energy by pumping water at motoring mode, and deliver the stored energy during demands at generating mode. The entire process does involve some financial loss, but availability based tariff compensates losses and generates more revenues [15].

The advantages of VS pumping operation is illustrated in Fig. 1a. For fixed impeller diameter of the pump, the operating domain at constant speed of any pump in term of head and flow rate is depicted in Fig. 1a [16]. The sub- and hyper-synchronous VS operation of pump significantly increases the operating range of PSP, as shown in Fig. 1. In pumps, the power consumption is proportional to the cube of speed, as shown in Fig. 1b. It is compulsory for the VS pumping operation to deal with available fluctuating power in grid,

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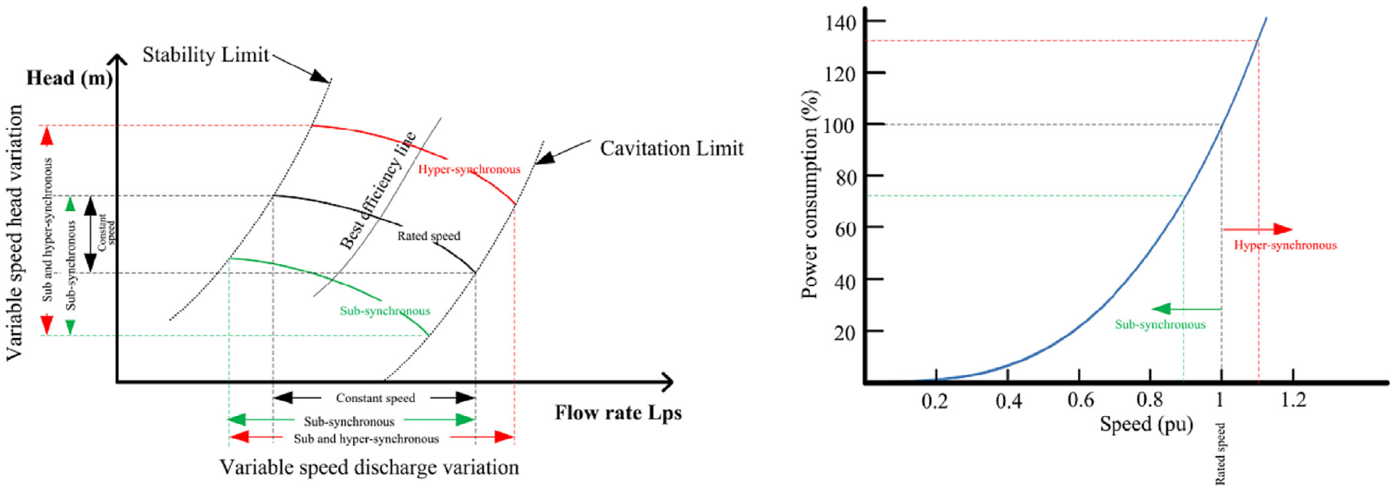

(a) Operating domain of pump with VS [16]   (b) Power consumption at various speeds

Fig. 1. The pump characteristics with VS technology.

produced by RES. This can be obtained through synchronous motor (either permanent magnet or electrical excitation) or DFIM [17,18]. These machines offer several advantages that include active power control in pumping mode, reactive power control at the interconnection point and instantaneous active power injection in the grid (fly-wheel effect) [19,20]. However, from the machine selection point of view, converter cost for speed control of machine is a very important index [19,21]. As speed variation of ±30% around the synchronous speed is usually required in pumping, the power rating of the converter is reduced in line with DFIM. When judged against fully-fed synchronous motor with full size converter for speed control, the DFIM put forward the advantage of VSD with four quadrants active–reactive power controls and lower power losses and converter cost [22]. The grid connected topology of DFIM with Rotor Side Converter (RSC) for speed (sub- and hyper-synchronous) and stator side reactive power input (Q_s) control is depicted in Fig. 2.

1.1. Literature review

Voltage sag is one of the severe PQ problems to be dealt with by the industrial power sectors. Voltage sags are usually linked with system faults but can also be caused by switching heavy loads or starting large motors [23]. The various classification of three-phase voltage sags are discussed in References [23,24]. Voltage sag causes severe process disruptions and sometimes electrical sensitive load often trip or shut-down resulting poor quality products

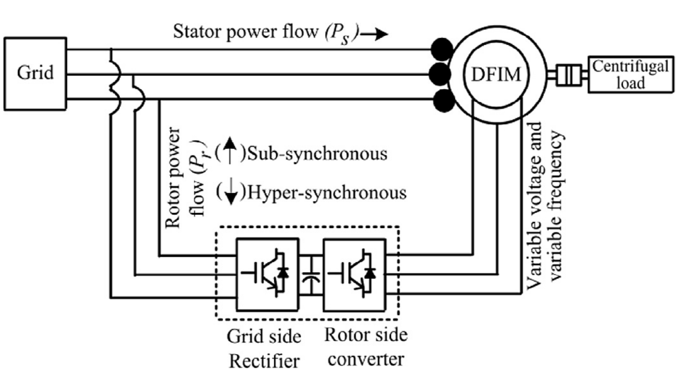

Fig. 2. DFIM topology for VS operation.

and substantial economic loss. In such a circumstance, it is crucial to know the PSP function when the voltage sag occurs and what methods are used for mitigating the effects of voltage sag.

Voltage sag's influence on DFIM at generating mode has been studied throughout the literature as this machine is widely used in remotely located wind farms [25–30]. The brief theoretical study for symmetrical and asymmetrical sag along with simulation validation is presented in Mohseni et al. [25]. There are two main problems that must be overcome in DFIM generating system during the voltage sag. The first one is the DC link overvoltage, and the second one is peak rotor fault current, which exceeds the Rotor Side Converter (RSC) limit. In wind firms crowbar protection is used, which is designed to operate for high transients in rotor currents caused by disturbance in stator voltage [26,27]. During crowbar operation rotor terminal is shortened and RSC is deactivated. Crowbar current settling time to zero has prominent impact of voltage recovery after fault. The detailed impact of the timings of crowbar removal and RSC reactivation on system voltage recovery is investigated in Foster et al. [26]. During crowbar operation, the machine behaves as conventional fixed speed induction generator, thus there is active and reactive power control failure. Rolan et al. [28] represent coordinated control of RSC and Grid Side Converter (GSC) to improve the low-voltage ride-through capability. The RSC and stator damping resistors are used to limit the peak rotor current and to reduce the oscillations and settling time during the voltage sags. Subsequently, the GSC is controlled to limit the DC-link overvoltage during voltage sags. In yet another study [29] a comprehensive description of symmetrical voltage sag effects on DFIM behavior in generating mode is discussed. Fault (sag) clearing process (abrupt or discreet voltage recovery) has a strong influence on rotor voltage as it controls the rotor current. Chondrogiannis and Barnes [30] develop the mathematical formulae for the peak rotor fault current and required rotor voltage magnitude under vector control. So far in literature, more emphasis is given to controller design to manage DC link over-voltage and rotor peak currents as it can cause the RSC failure; this may further weaken grid performance.

Zhang and Ooi [31] show that doubly-fed induction generator used in wind farms is appropriate for motoring operation also. This adoption is straightforward and requires three-phase autotransformer for starting. The same back-to-back converter can be utilized for full speed ranges that were being employed during generating mode. Theoretically, DFIM can work up to twice of the

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