Nyquist Stability Criterion Based SSR Explanation for Type 3 Wind Generators

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***Abstract*—Type 3 wind generators in series compensated networks could lead to subsynchronous resonance (SSR) oscillations - a phenomenon observed recently. In this letter, impedance-based Nyquist stability criterion is applied to explain the phenomena. The explanation corroborates the authors' previous explanation of self excitation using net negative resistance concept. Nyquist map is also able to demonstrate the impact of wind speed on SSR.**

***Index Terms*—Subsynchronous resonance, Doubly Fed Induction Generator, Wind Generation**

I. INTRODUCTION

Subsynchronous resonance (SSR) oscillations were observed in Type 3 wind farms by the industry recently. In [1], an event led to such phenomena was described and the recorded voltage and current waveforms with SSR oscillations are presented. A type 3 wind farm is connected to a transmission path with two parallel lines. One line is equipped with series compensation (fixed capacitors). Due to a fault, the other line was tripped and the compensated line is directly connected to the wind farm. SSR oscillations started and kept increasing.

SSR phenomena in series compensated Type 3 wind have been modeled in the author's research [2]. The conclusions from [2] can be summarized as follows:

- Torsional interactions between the network mode and the wind turbine torsional mode are rare. This is because the wind turbine has soft shaft and the frequency of the torsional mode is quite low ($<$ 3 Hz). In order to have torsional interactions, the network has to have a very high compensation level to reach a high network frequency ($>$47 Hz).
- Induction generator effect is the major cause of SSR. This could be due to a negative slip at the SSR frequency which leads to a negative equivalent rotor resistance at low wind speeds. The negative feedback current controls also have adverse impact on stability.

The objective of this letter is to apply the impedance modeling technique in Type 3 wind generator SSR phenomena. Nyqusit stability criterion will also be applied to detect SSR. The letter will also show that negative net resistance is in fact equivalent to Nyquist instability.

II. IMPEDANCE BASED NYQUIST STABILITY CRITERION

Impedance based small signal analysis has been applied in power electronic converter analysis in [3], [4]. For a system

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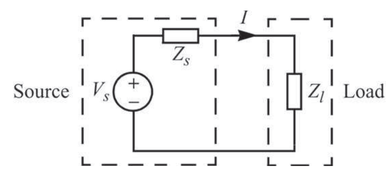

Fig. 1. Small signal representation of a voltage source and a load [3].

with a source impedance and load impedance as shown in Fig. 1, the current can be found

$$I(s) = \frac{V(s)}{Z_s(s)+Z_l(s)} \tag{1}$$

$$= \frac{V(s)}{Z_l(s)}.\frac{1}{1+Z_s(s)/Z_l(s)} \tag{2}$$

Assume that the voltage source is stable and the load is stable when powered from an ideal voltage source, then for the system to be stable, the denominator $1+Z_s(s)/Z_l(s)$ should have all zeros in the open LHP. Based on Nyquist stability criterion, if and only if the number of counter-clockwise encirclement around $(-1+j0)$ of Z_s/Z_l is equal to the number of the RHP poles of Z_s/Z_l , the system will be stable. In cases when Z_s/Z_l has no RHP poles, the Nyquist map of Z_s/Z_l should not encircle $(-1+j0)$.

Instability happens when Z_s/Z_l encircles $(-1+j0)$. This can be expressed as there exists a frequency ω_0 which can make $Z_s(j\omega_0)/Z_l(j\omega_0) < -1$, or

$$\begin{aligned} Z_s(j\omega_0) &= R_s + jX_s \\ &= -KZ_l(j\omega_0) = -K(R_L + jX_L) \end{aligned}$$

where K is a real number and $K > 1$. Hence

$$R_s + R_L < R_s + KR_L = 0.$$

Therefore, Nyquist instability corresponds to negative net resistance. Negative net resistance has been used to explain and detect IGE using frequency scan method in the literature.

III. SSR NYQUIST EXPLANATION

Nyquist stability criterion will be used to explain SSR phenomena in Type 3 wind generator. A study system consisting of a Type 3 wind generator with partial back-to-back voltage source converters and series compensated network has been studied in [2] and shown in Fig. 2.

In order to find the two impedances, the per phase equivalent circuit of the system is shown in Fig. 3. Assumptions are made to simplify the system: the shunt branch with the

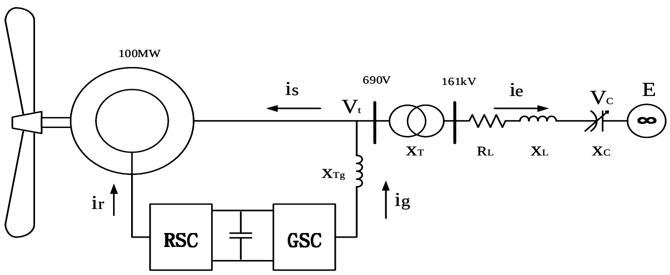

Fig. 2. The study system in [2].

grid side converter is ignored and the shunt branch of the magnetizing inductance of the induction machine is ignored. Both assumptions are reasonable since the impedances are very large compared to the parallel branches. In this analysis, the rotor side converter controller's current control loop gains are assumed to be very small. Hence the equivalent impedance of the RSC is ignored. This assumption is to simply the circuit for illustration only. Detailed impedance modeling will be conducted in further research to demonstrate the impact of converter control on SSR.

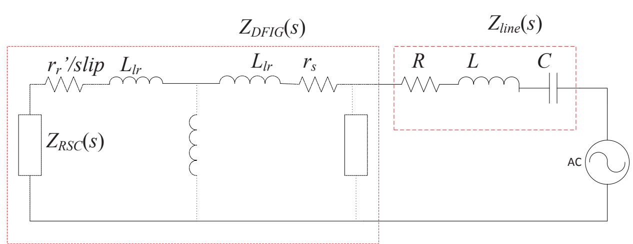

Fig. 3. The equivalent circuit.

The impedance of the series compensated line can be represented by

$$Z_{line}(s) = R + Ls + \frac{1}{Cs} \tag{3}$$

The impedance of the Type 3 wind generator is dependent on the slip and stator frequency ω. Slip is related to the rotating speed ω_m and the stator frequency ω. For the electric circuit analysis, the rotating speed can be assumed to be constant since mechanical dynamics is much slower than the electric dynamics. Slip can be expressed as $1 - \omega_m/\omega$. In Laplace domain, slip can be expressed as

$$slip(s) = \frac{s - j\omega_m}{s}. \tag{4}$$

Hence the impedance of the DFIG seen from its terminal can be represented by:

$$Z_{DIFG}(s) = r_r/slip(s) + r_s + (L_{ls} + L_{lr})s. \tag{5}$$

In the SSR study case, Z_{line} is the source impedance and Z_{DFIG} is the load impedance. Hence Nyquist map of Z_{line}/Z_{DFIG} will be studied.

IV. Nyquist Map

Using the same study system and same parameters as in [2], two impedances are derived and the Nyquist map of Z_{line}/Z_{DFIG} is plotted in Fig. 4. It is shown that when the rotating speed at 0.7 pu, the Nyquist map will encircle $(-1+j0)$ which indicates instability. When the rotating speed is at 0.8 pu and 0.9 pu, there is no SSR stability issue. The resonant frequency is about 40 Hz, which corresponds to the LC resonant frequency at 75% compensation level. This analysis corroborates the conclusion drawn from eigenvalue based analysis in [2]. However the prediction of SSr is more conservative since the shunt branches are ignored.

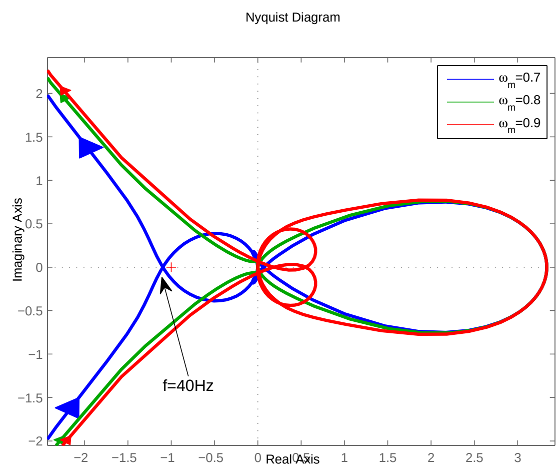

Fig. 4. Nyquist map for different rotating speeds. Series compensation level: 75%.

The Nyquist map demonstrates the effect of wind speed on SSR stability since low wind speed corresponds to low rotating speed. Hence Type 3 wind generator is more prone to SSR when wind speed is lower.

V. Concluding Remarks

This letter applies impedance based Nyquist stability analysis to study Type 3 wind generator SSR stability problem. Impedance models for a DFIG and a RLC network are first developed. Nyquist stability criterion is then applied to explain the phenomena. The impedance based Nyquist map demonstrates the impact of wind speed on SSR stability in Type 3 wind generator.

References

[1] G. Irwin, A. Jindal, and A. Isaacs, "Sub-synchronous control interactions between type 3 wind turbines and series compensated ac transmission systems," in *IEEE Power & Energy General Meeting 2011*, Jul. 2011.

[2] L. Fan, R. Kavasseri, Z. Miao, and C. Zhu, "Modeling of dfig-based wind farms for ssr analysis," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2073–2082, Oct. 2010.

[3] J. Sun, "Impedance-based stability criterion for grid-connected inverters," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3075–3078, Nov. 2011.

[4] ——, "Small-signal methods for ac distributed power systems a review," *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2545–2554, Nov. 2009.