다중 SOGI-FLL 기반 엔진-발전기 시스템의 속도 추정

다오녹닷, 이동춘
영남대학교 전기공학과

Speed Estimation of Diesel-Generator Systems Based on Multiple SOGI-FLLs

Ngoc Dat Dao and Dong-Choon Lee
Department of Electrical Engineering, Yeungnam University

ABSTRACT

This paper proposes a speed estimator for sensorless control of diesel-generator (genset) systems, where the speed of the genset is calculated from the back-EMF frequency of the generator. The back-EMF frequency is extracted from a phase output current by using multiple second-order generalized integrators (SOGIs) connected in parallel and series and separated frequency-locked loops. The proposed method (PS-SOGI-FLL) is able to estimate the fundamental frequency in the distorted output current with high accuracy and strong robustness. Simulation results are shown to verify the validity of the proposed method.

1. Introduction

Variety of position/speed sensorless control schemes have been proposed in literature. Most of the methods are applied for the systems with a PWM converter, where the currents of the generator are controlled to be sinusoidal and the speed and position of generator are estimated based on the generator model. However, in some applications where the output of the generator is connected with a diode rectifier, the output current of the generator is distorted due to high-order harmonic components [1]. Therefore, it is necessary to develop a method to estimate the back-EMF frequency from the output current accurately with a strong immunity against the high-order harmonic components.

In this study, in order to extract the back-EMF frequency accurately from a phase current of the generator connected with a diode rectifier, a novel method is proposed which consists of multiple SOGI-FLL connected in parallel and series. The method uses multiple parallel SOGI-FLLs as pre-filters to eliminate the fifth-order harmonic since it is the dominant harmonic component in the current signal [1]. Then the output of the multiple SOGI-FLL is fed to a single standard SOGI-FLL so that other unknown harmonics can be attenuated. The proposed method utilizes two separate FLL blocks, which is different from the existing methods [2], [3] where only one FLL block is used for all SOGIs. That brings an advantage of a degree of freedom for tuning FLLs to achieve faster dynamic response without reducing the immunity to harmonics components. In addition, by using two FLLs, the system is more stable and robust to the frequency disturbance than if only one FLL is used. The proposed method is verified by simulation results with a comparison to other existing methods.

2. Proposed PS-SOGI-FLL

2.1 Structure of PS-SOGI-FLL

The structure of the proposed method comprises of multiple SOGI-FLL connected in parallel and series to obtain better filtering capability with lower computational burden compared with the case when only either parallel SOGI-FLLs[4] or series SGOGI-FLLs[2] are used. In addition, the proposed structure utilizes a separated FLL block for each SOGI block connected in series to achieve fast response of frequency estimation and high robustness against frequency variations.

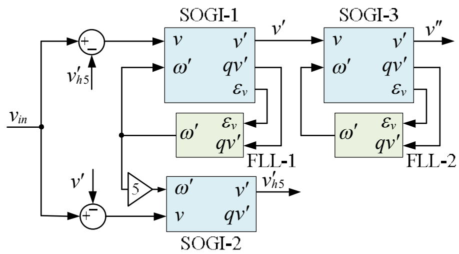

Fig. 1. Block diagram of proposed PS-SOGI-FLL.

Fig. 1 shows the proposed MC-SOGI-FLL used for extracting the back-EMF frequency from the output current of the generator in genset systems. The proposed structure consists of three blocks of SOGIs and two FLL blocks. Two SOGIs are connected in parallel to extract the fundamental and fifth-order harmonic components. Since the fifth-order harmonic component is dominant in the output currents, only one SOGI block is tuned at the fifth-order harmonic frequency.

2.2 Analysis of PS-SOGI-FLL

If the input signal contains high-order harmonics, the state variables of the first SOGI-FLL have the relationship as

$$\dot{\bar{x}}_1 = -\omega^2 \bar{x}_{21} - \omega^2 \sum h^2 \bar{x}_{2h} \tag{1}$$

where h is an odd integer number (5, 7, 11, 13), which means the order number of harmonic components in the input signal. The bar over the variables represents for steady-state values.

The steady-state error signal can be expressed as

$$\bar{\varepsilon}_v = \left(v - \bar{x}_1\right) = \frac{1}{k\omega'}\left(\dot{\bar{x}}_1 + \omega'^2 \bar{x}_2\right). \tag{2}$$

Substituting (1) into (2), the steady-state frequency error is obtained as

$$\bar{\varepsilon}_f = \omega' \bar{x}_2 \bar{\varepsilon}_v = \frac{\bar{x}_2^{\,2}}{k}\left(\omega'^2 - \omega^2\right) - \underbrace{\frac{\bar{x}_2}{k}\omega^2 \sum (h^2 - 1)\bar{x}_{2h}}_{\Delta\bar{\varepsilon}_{fh}}. \tag{3}$$

The dynamics of the FLL is given by

$$\dot{\omega}' = -\gamma\bar{\varepsilon}_f = -\frac{\gamma}{k}\bar{x}_2^{\,2}\left(\omega'^2 - \omega^2\right) + \gamma\Delta\bar{\varepsilon}_{fh}. \tag{4}$$

If the value of γ is normalized according to

$$\gamma = \frac{k\omega'}{v'^2 + qv'^2}\Gamma, \tag{5}$$

then, the averaged dynamics of the FLL can be expressed as a first-order transfer function as

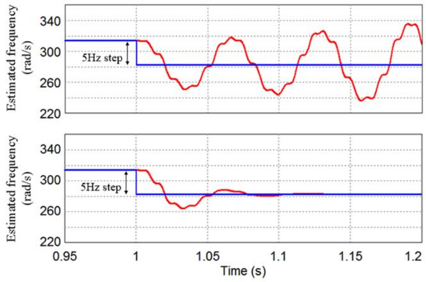

Fig. 2. Estimated frequency obtained by two series SOGIs with a single FLL (top) and with two FLLs (bottom) for a frequency step disturbance from 50 Hz to 45 Hz.

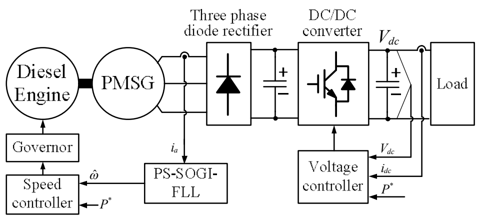

Fig. 3. Block diagram of proposed PS-SOGI-FLL.

$$\frac{\bar{\omega}'}{\omega}(s) = \frac{\Gamma}{s+\Gamma}. \tag{6}$$

As seen in (4), if the input signal contains harmonic components, the frequency estimation will have oscillations due to the second term of the right-hand side in (4). In the proposed method, only one SOGI is used to cancel the 5th order harmonic to reduce the computational time. Thus, there are still 7th, 11th and 13th harmonics in the output signal of the first SOGI, which generate harmonic ripples in the frequency estimation. From (4), a high value of γ (or Γ) will make the FLL performance fast, but the harmonic ripples in the estimation will be high.

The proposed method uses two separated FLLs which is different from the method proposed in [2] where only one FLL is used for all SOGIs. The advantage of using two separated FLLs is that the gain Γ can be set differently for two FLLs. In this case, Γ_2 is set to much higher than Γ_1 to make the speed estimation faster. If only one FLL is used at the third SOGI, then the gain Γ is limited by the bandwidth of the second-order SOGI (a series of two SOGIs) which is narrower than that of the first-order SOGI (a single SOGI).

Fig. 2 shows the behavior of two series SOGIs with a single FLL [2] and the proposed method with two separated FLLs. For the single FLL, the gain $\Gamma = 200$ and for the two separated FLLs $\Gamma_1 = 50$ and $\Gamma_2 = 200$. As seen from Fig. 2, with the same disturbance of 5 Hz in the frequency of the input signal, the estimated frequency settles to 45 Hz after 0.1s when using two FLLs, but the output of the single FLL oscillates and it is unstable.

3. Simulation Results

To verify the proposed method for speed estimation, a simulation is carried out using the PSIM for a 100-kW variable-speed genset system, where the block diagram of the system is illustrated in Fig. 3. In the PS-SOGI-FLL (Fig. 4), the first SOGI is used to extract the fundamental component of the input signal, which is the output current of the generator. The second SOGI is tuned at 5th order harmonic to eliminate that component. Finally, the third SOGI is utilized to enhance the filter capability against

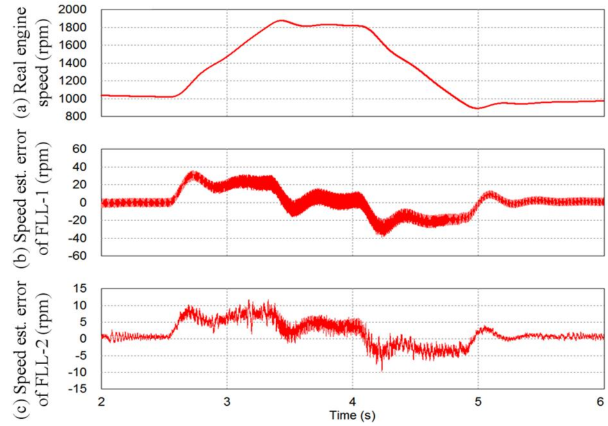

Fig. 4. Performance of PS-SOGI-FLL. (a) Real engine speed. (b) Speed estimation error in FLL-1. (c) Speed estimation error in FLL-2.

the 7th, 11th, 13th order harmonics and the DC component. The gains for SOGI-1, SOGI-2 and SOGI-3 are $k_1 = 1$, $k_2 = 0.2$ and $k_3 = 0.5$, respectively. The gains for FLL-1 and FLL-2 are $\Gamma_1 = 50$ and $\Gamma_2 = 200$, respectively.

Fig. 4 shows the speed estimation performance when the engine speed varies. The estimated speed is utilized for engine speed control. During the change of speed, the tracking errors of the speed estimator by FLL-1 and FLL-2 are about 20 rpm and 5 rpm, respectively. The errors produced by FLL-2 is four times lower than that of FLL-1 since the gain Γ_2 is four time higher than Γ_1. The speed value obtained by FLL-1 has ripples of 10 rpm ~ 20 rpm due to the harmonic components of the generator current. The average value of the estimation errors are zero when the engine is operated in steady-state condition.

4. Conclusions

In this paper, a novel speed estimation has been proposed for variable-speed diesel-engine generator systems. In the proposed PS-SOGI-FLL method, the speed is estimated by extracting the frequency of a generator output current, which is highly accurate even though the distorted currents exist due to diode rectifier connection. The proposed method can effectively eliminate not only harmonic components but also DC components. Furthermore, the proposed method is more robust to frequency disturbances than other existing methods. The effectiveness of the proposed method has been verified by simulation results.

References

[1] B. Wu, *High Power Converters and AC Drives*, 1st ed. Wiley-IEEE Press, 2006, pp. 38-47.

[2] J. Matas, M. Castilla, J. Miret, L. Garcia De Vicuna, and R. Guzman, "An adaptive prefiltering method to improve the speed/accuracy tradeoff of voltage sequence detection methods under adverse grid conditions," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, pp. 2139–2151, 2014.

[3] Z. Xin, X. Wang, Z. Qin, M. Lu, P. C. Loh, and F. Blaabjerg, "An Improved Second-Order Generalized Integrator Based Quadrature Signal Generator," *IEEE Trans. Power Electron.*, vol. 31, no. 12, pp. 8068–8073, 2016.

[4] P. Rodríguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 127–138, 2011.