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A Frequency Control Strategy Using Power Line Communication in a Smart Microgrid

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ABSTRACT This paper presents an application of power-line communication (PLC) as a viable solution for frequency regulation in a smart microgrid. The microgrid under consideration comprises a diesel generator with a frequency controller and another synchronous generator operating in the constant power mode. Frequency regulation is achieved in the microgrid by communicating the frequency deviation (information) from the control center to the diesel generator using PLC. The information received at the other end is used for frequency regulation. A simple yet effective M-ary amplitude-shift keying (ASK) modulation-based PLC system is proposed for information transmission. A comparative analysis of M-ary ASK and M-ary frequency-shift keying (FSK)-based PLC systems is also presented. Approximate closed-form expressions for the average symbol error rate and the average achievable rate are derived for both the PLC systems, assuming that the PLC channel coefficients and the additive impulsive noise samples are derived from a log-normal distribution and a Bernoulli–Gaussian process, respectively. The results show that M-ary ASK is a better choice for PLC than M-ary FSK. Furthermore, the delay introduced in the control loop while using the proposed PLC system is negligible, and therefore, the stability of the microgrid is also ensured.

INDEX TERMS Amplitude shift-keying (ASK), diesel generator (DG), frequency control, frequency shift-keying (FSK), governor, power line communication (PLC), smart microgird.

I. INTRODUCTION

Power system operation requires proper control of key parameters such as frequency, voltage, and active and reactive powers. In a conventional power system, the area control error (ACE) is communicated to the generating unit for controlling the active power generation in a control area. The received ACE is then used by the controller to achieve frequency regulation and controlled tie-line power flow. Even in a smart microgrid, the same principle of communicating error information from the control center to the generating unit exists. The need of a communication system for frequency control in a smart microgrid is discussed in [1]. If a phasor measurement unit (PMU) or any frequency sensing device is used at a control center to monitor the system states, then the same can be transmitted to the generating unit(s) using intelligent communication techniques, and thus the requirement of various types of equipment for measuring global parameters such as frequency can be avoided.

A communication system plays a crucial role in transferring the required information from the control center to the generating unit. An amalgamation of a power system, an intelligent controller, and communications engineering results in a concept called smart grid, and hence reviewing the contenders of communication solutions is necessary here. Various research articles [2]–[6] discuss about impacts of communication delays on the effective control of a power system, particularly from the stability point of view, but not much of these have presented how an intelligent communication scheme can actually be applied for frequency regulation in a power system, particularly in a microgrid. Furthermore, the challenges and implementation procedures of viable communication systems along with their validation are not presented. For a smart grid, power line communication

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(PLC) based systems which use existing power cables to carry information along with the main power signal is a feasible option. The main power signal is transferred at low frequency (50 or 60 Hz), whereas the PLC information signal is transferred at a much higher center frequency with comparatively much less power without affecting the main power signal. As PLC systems use the existing infrastructure of the utility, it is often referred to as a retrofit technology. High signal attenuation in PLC, which is considered as a drawback for a communication channel, provides an advantage for limiting the interference over a particular geographical area. Hence, it also provides physical layer security. However, to increase the coverage using PLC, various multi-hop communication techniques can be opted [7]–[9].

The bands available for PLC are categorized as narrowband and broadband wherein $3 - 500$ kHz is reserved for narrowband and $2 - 30$ MHz for broadband PLC systems [10]. For control applications, narrowband PLC systems are preferred owing to their support for extended range with low data rates. Similar to fading in wireless channels, the power received at the receiver through PLC channels also fluctuates with time due to reflections of the signal at various load terminals, and the distributions of the fading amplitudes are shown to be log-normal [11]–[13]. Unlike the additive white Gaussian noise (AWGN) channel in wireless communication, signal transmission through PLC suffers from impulsive noise as well. Thus, for performance analysis, the behavior of the additive noise in PLC is well modeled by the Bernoulli-Gaussian process [8], [14]–[16].

It is well known that digital communication is superior over analog when compared for reliability with same average transmission power [17]. Among several carrier-based digital transmission schemes, M-ary amplitude-shift keying (ASK) is most popular for its simple modulator and demodulator structures [18]. In general, bandwidth efficiency of M-ary ASK is superior to that of M-ary frequency-shift keying (FSK) at the cost of power efficiency [17]. Therefore, a comparative physical layer performance analysis between M-ary ASK and M-ary FSK is presented in this paper to prove the same for PLC. Thus, keeping the facts in hand that narrowband PLC has limited bandwidth and supports signal transmission at comparatively higher signal-to-noise ratio (SNR), a 64 level ASK based PLC system is proposed for information exchange. Since the received signal power varies depending on the load and the length of the power network, a reference signal is also used to scale the amplitude of the received signal to extract the information from the amplitude of the demodulated signal. Typical applications of PLC for control purposes in AC/DC microgrids have been demonstrated in [18]–[20]. However, beyond small microgrids of few generators and loads, the application of PLC for controlling larger microgrids with multiple rotating generators and a meshed network is yet to be explored.

Keeping the above discussions in view, this paper presents a frequency control scheme in a smart microgrid having two diesel generators with governor for frequency regulation. The power system considered is a 15 bus microgrid, wherein the generators are placed at different buses while the control center is located at some other bus. The frequency deviation is sent from the control center to the diesel generators using an M-ary ASK based PLC system along with a reference signal for adaptive gain control of the communication signal. The signal is received at the diesel generator terminals and is given to the respective governor which regulates the mechanical power generated by the diesel engines which in turn controls the frequency of the system. A simple phase locked loop (PLL) is used to measure the system frequency at the bus where the control center is located.

II. SYSTEM MODEL

The power system under consideration consists of a 400 V, 3-phase, 50 Hz, 15 bus distribution system, and Fig. 1 shows the single line diagram of the same. A diesel engine generator with a governor for the power system frequency control is connected to bus 1.

The diesel engine is equipped with a governor to control the mechanical power developed by the engine in order to achieve frequency regulation. A typical diesel engine governor control is shown in Fig. 2b. The governor takes per unit (p.u.) ΔF or p.u. change in speed ($\Delta\omega$) signal as input and controls the diesel engine mechanical power. The diesel engine governor parameters are as follows: $a_0 = 0.2$,

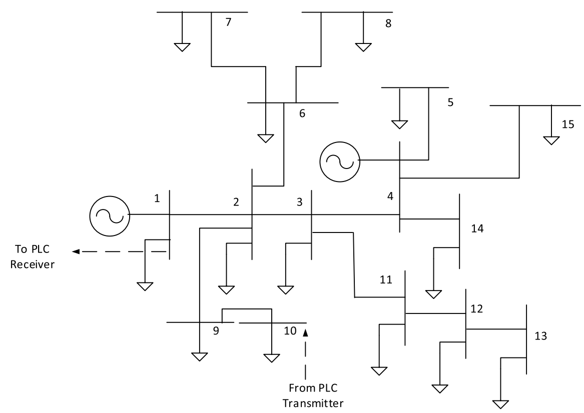

FIGURE 1. 15 bus microgrid under study.

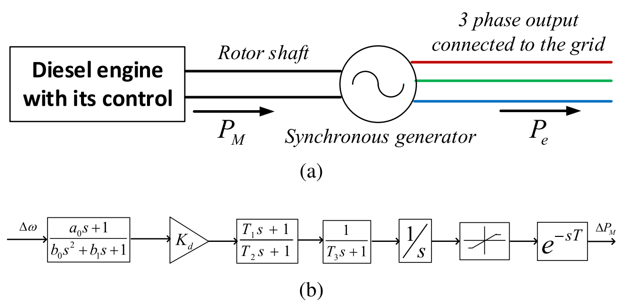

FIGURE 2. Frequency control of diesel engine generator system. (a) Operation of diesel engine driven synchronous generator. (b) Modeling of diesel engine with governor.

$b_0 = 0.0002$, $b_1 = 0.01$, $K_d = 120$, $T_1 = 0.25$, $T_2 = 0.009$, $T_3 = 0.0384$, and $T = 0.024$.

Another synchronous generator is connected to bus 4 which is first assumed to be a fixed power generator i.e the engine is without governor and does not participate in frequency control. However, in a latter study, the same diesel engine generator system is also considered with governor control in order to show the PLC performance when multiple generators are involved in frequency control. Furthermore, the control center is assumed to be at bus 10 and the power signal frequency at this bus is sensed using a PLL to calculate the frequency error, denoted as ΔF. The analog error signal is then converted to a digital signal and transmitted using a PLC transmitter (described later in detail) in one of the phases (phase A in this study) at this bus. The same is received at the diesel generator at bus 1 and converted back to analog for further use. The communication signal, shown by dashed lines in Fig. 1, is injected into the network at bus 10 and received from the network at bus 1. The line resistance and inductance for the various lines shown in Fig. 1 are given in Table 1.

TABLE 1. Line parameters.

From bus	To bus	R (Ω)	L (mH)
1	2	0.0676	0.2107
2	3	0.0585	0.1822
2	6	0.1278	0.2746
2	9	0.1006	0.2162
3	4	0.0420	0.1310
3	11	0.0897	0.1928
4	5	0.0761	0.1636
4	14	0.1115	0.2396
4	15	0.0598	0.1285
6	7	0.0544	0.2761
6	8	0.0625	0.1344
9	10	0.0843	0.1810
11	12	0.1224	0.2629
12	13	0.1006	0.2162

III. COMMUNICATION SYSTEM

The communication system described here consists of an analog-to-digital converter (ADC), an ASK modulator, a coupling circuit, an ASK demodulator, and a digital-to-analog converter (DAC) [18]. For the information signal gain control at the receiver side, a reference carrier signal with a constant amplitude is sent along the ASK signal.

A. ADC

The error signal that needs to be transmitted through the PLC is analog in nature, and hence it is required to convert the analog error signal to digital signal. In this particular application, the error signal (ΔF) variation is considered to be typically between ± 0.03 per-unit for average load changes. The desired analog error signal is converted to a 64 level digital signal with a sample time of 1 ms in two stages. In the initial stage, the analog error signal is sampled at a regular interval of 1 ms and later, the sampled signal is quantized to the nearest level. For this application, the total number of levels selected is 64, and hence each sample after quantization is a digit of the size $\log_2(64) = 6$ bits. Thus, the ADC produces a digital signal every 1 ms and each sample is of size 6 bits.

B. M-ARY ASK MODULATOR

ASK is one of the basic and simplest digital modulation techniques. In ASK, the amplitude of carrier signal is modulated in agreement with the information signal similar to that of analog amplitude modulation. Contrary to analog amplitude modulation, the information signal has fixed levels in M-ary ASK. For this particular application, the M-ary ASK modulator takes 6 bits at a time and changes the carrier amplitude corresponding to the level represented by those 6 bits. The phase and the frequency of the carrier remain same for all the information signals. In this model, the carrier frequency is chosen to be 500 kHz. Apart from the information signal (error signal) transmitted at 500 kHz, a reference signal is also transmitted with a constant amplitude and a carrier frequency of 300 kHz.

C. COUPLING CIRCUIT

This block is one of the essential parts of a PLC system, and it is considered as an interdisciplinary block. This block interfaces the digital communication system with the power system. The major role of this coupling circuit is to prevent low-frequency signals, in particular, 50 Hz/60 Hz AC signals from entering into the communication system. Furthermore, it also injects the M-ary ASK signals into power lines without disturbing the 50 Hz/60 Hz power signal. This block consists of a high-pass filter with an inductive coupler. The high-pass filter only allows the communications signal to pass through and blocks the 50 Hz/60 Hz power signal. Thus, the inductive coupler isolates the power line from the communication system. Moreover, it injects the M-ary ASK signal into the power line at the transmitter and extracts it back from the power line at the receiver.

D. M-ARY ASK DEMODULATOR

For the system under consideration, a coherent demodulator is chosen because a reference signal is also present along with the information signal. The received signal is first passed through two multipliers in parallel and then passed through envelope detectors (EDs). The second input to the first and second multipliers are the carrier signals of the frequencies 500 kHz and 300 kHz, respectively. Thus, the information signal is recovered at the output of the first ED, and the reference signal from the second.

Before feeding the recovered information signal to the decision maker, it is required to scale the signal to compensate the attenuation due to path loss and load change. As the reference signal voltage is known to the receiver, it calculates the attenuation factor and then scales the information signal accordingly. The scaled information signal is then passed through the decision maker, and the signal waveform is mapped to its original level by making a comparison between the recovered waveform with the predefined thresholds. These levels are then converted to bits for further processing and sent to the DAC.

E. DAC

The input to the controller is an analog signal, and hence the digital signal received at the receiver is converted back to the analog signal. The DAC takes 6 bits at a time and generates the corresponding analog value which is sent to the controller.

F. PHYSICAL LAYER ANALYSIS OF THE PLC SYSTEM

In this section, we investigate two important performance measures, the average SER and the average achievable rate, of the PLC system employing M-ary ASK and M-ary FSK. For M-ary ASK, information is transferred by scaling the amplitude of the pulse corresponding to the information symbol and the pulse is then transmitted using a carrier with a single frequency. As the carrier frequency remains the same and only the amplitude of the pulse changes, this modulation scheme is one-dimensional. On the other hand, in M-ary FSK, information is transferred by selecting one of M orthogonal carrier frequencies corresponding to the information symbol. Since the pulse amplitude remains the same for all symbol transmissions and the carrier frequency changes, this modulation scheme is M-dimensional [17].

Consider the transmission of the information symbols using the M-ary ASK signaling scheme. Assuming that all the information symbols are equally probable and there are M such symbols, an information symbol can be represented by the waveform given as [17]

$$x_m(t) = A_m p(t), \quad 0 \le t < T_s, \tag{1}$$

where $p(t)$ is a pulse of duration T_s seconds with support $[0, T_s)$ and energy E_p, and $A_m = 2m - 1 - M$ is the amplitude of the mth information symbol, $m = 1, \ldots, M$. Thus, the energy in the signal $x_m(t)$ is given by

$$E_m = \int_{-\infty}^{\infty} A_m^2 p^2(t) \mathrm{d}t = A_m^2 E_p \,. \tag{2}$$

The average energy per symbol can therefore be calculated as

$$E_{avg} = \frac{1}{M} \sum_{m=1}^{M} A_m^2 E_p = \frac{(M^2-1)E_p}{3} \,. \tag{3}$$

Furthermore, the average energy per bit per symbol is given by

$$E_{b_{avg}} = \frac{(M^2-1)E_p}{3\log_2(M)} \,. \tag{4}$$

Now consider simultaneous transmission of the M-ary ASK information signal $x_m(t)$ and reference signal $x_r(t)$ over different carriers with frequencies ω_i and ω_r, respectively. The received signal $y(t)$, at the receiver can therefore be expressed as

$$\begin{aligned} y(t) &= h(t)\left(x_m(t)\cos(\omega_i t) + x_r(t)\cos(\omega_r t)\right) + n(t) \\ &= h(t)\left(A_m p(t)\cos(\omega_i t) + A_r p(t)\cos(\omega_r t)\right) + n(t), \end{aligned} \tag{5}$$

where A_m and A_r represent the amplitudes of the information and the reference signals, respectively, and $h(t)$ and $n(t)$ represent the PLC channel gain and the additive impulsive noise, respectively. The sampled values of the information and the reference signals, denoted by y_i and y_r, at the output of the first and second envelope detectors, respectively, are given by

$$\begin{aligned} y_i &= \sqrt{E_m} h + n, \\ y_r &= \sqrt{E_r} h + n, \end{aligned} \tag{6}$$

where h and n are the sampled values of the channel gain and the additive noise, respectively. Furthermore, E_m and E_r are the energies of the information and the reference signals, respectively. As the reference signal is already known to the receiver, at high SNR, the channel gain h can be calculated from y_r and it can be used to normalize the effect of the channel from y_i as

$$\hat{x}_i = \frac{y_i}{h} = \sqrt{E_m} + \frac{n}{h}. \tag{7}$$

After that, the decision maker maps $\hat{x}_i$ to any of the 64 levels by making a comparison with the predefined thresholds.

It has been shown that for PLC, h follows a log-normal distribution with probability density function (p.d.f.) given by [11]–[13]

$$f_h(v) = \frac{(1/v)}{\sqrt{2\pi\sigma_h^2}} \exp\left(-\frac{1}{2}\left(\frac{\ln v - \mu_h}{\sigma_h}\right)^2\right), \quad v > 0. \tag{8}$$

Unlike the AWGN channel in a wireless communication system, the additive noise in PLC is shown to have impulsive contents as well [10], [21]. The additive impulsive noise of the PLC channel can be modeled by a Bernoulli-Gaussian process [14], [16] and the noise sample n can be expressed as

$$n = n_G + b_I n_I, \tag{9}$$

where n_G and n_I follow zero-mean Gaussian distributions with variances σ_G^2 and σ_I^2, respectively, and b_I follows the Bernoulli distribution with parameter p. Samples n_G, n_I, and b_I are assumed to be independent as their sources are different. The average noise power can be given as

$$N_0 = E\left[n^2\right] = \sigma_G^2(1 + p\eta), \tag{10}$$

where $\mathbf{E}[\cdot]$ denotes expectation and $\eta = \sigma_I^2/\sigma_G^2$ denotes the *power ratio of impulsive noise to background noise*. Hence, the p.d.f. of n is given by

$$f_n(\nu) = \sum_{j=1}^{2} \frac{p_j}{\sqrt{2\pi\sigma_j^2}} \exp\left(-\frac{\nu^2}{2\sigma_j^2}\right), \quad \infty < \nu < \infty, \tag{11}$$

where

$$p_1 = 1 - p, \quad p_2 = p, \quad \sigma_1 = \sigma_G, \quad \sigma_2 = \sqrt{\sigma_G^2 + \sigma_I^2}. \tag{12}$$

The SNR is expressed as

$$\gamma = \frac{E_{avg}\, h^2}{N_0} = \frac{E_{avg}\, \beta}{N_0}, \tag{13}$$

where $\beta = h^2$. As h is log-normal with parameters μ_h and σ_h, β in (13) follows a log-normal distribution (8) with parameters μ_β and σ_β given by

$$\mu_\beta = 2\mu_h, \quad \sigma_\beta = 2\sigma_h. \tag{14}$$

1) AVERAGE SER ANALYSIS

The average SER for the M-ary ASK based PLC system in the presence of Bernoulli-Gaussian noise is given in approximate closed-form by [18]

$$\mathcal{P}_{M-ASK} \approx \left(1 - \frac{1}{M}\right) \sum_{j=1}^{2} \sum_{k=1}^{K} \frac{C_{j,k}}{A_k} Q\left(\frac{B_{j,k}}{\sqrt{1 + A_k^2}}\right), \tag{15}$$

where $Q(\cdot)$ denotes the Gaussian Q-function, and

$$\begin{aligned} A_k &= \sqrt{\frac{4\sigma_h^2}{R3_k^2}}, \\ B_{j,k} &= \frac{8\sigma_h\left(2\mu_h + \ln \frac{\alpha_j 3E_{avg}/N_0}{M^2-1} - R2_k\right) - 2\sigma_h R3_k^2}{2A_k R3_k^2}, \\ C_{j,k} &= R1_k \sigma_h p_j \sqrt{\alpha_j \frac{6E_{avg}/N_0}{M^2 - 1}} \times \exp\left(\frac{2\mu_h + B_{j,k}^2}{2}\right) \\ &\quad \times \exp\left(-\left(\frac{2\mu_h + \ln \frac{\alpha_j 3E_{avg}/N_0}{M^2-1} - R2_k}{R3_k}\right)^2\right), \\ \alpha_1 &= \frac{1 + p\eta}{2}, \quad \alpha_2 = \frac{1 + p\eta}{2(1 + \eta)}, \end{aligned} \tag{16}$$

and $R1_k$, $R2_k$, and $R3_k$ in (16) are the real constants that are tabulated in [15, Table 2]. It has also been calculated in [15] that $K = 4$ is sufficient for the approximation with a root mean squared error of 4.48×10^{-4}.

2) SER FOR M-ARY FSK

In M-ary FSK signaling, the transmission of information takes place by selecting a unique frequency corresponding to the symbol. The instantaneous SER for M-ary FSK is expressed as [17]

$$\mathcal{P}_{M-FSK}(\gamma) = \sum_{j=1}^{2} \sum_{m=1}^{M-1} p_j \frac{(-1)^m}{(m+1)} \binom{M-1}{m} \exp\left(-\frac{m \log_2(M) \alpha_j \gamma}{(m+1)}\right), \tag{17}$$

where p_j and α_j are given by (12) and (16), respectively. Given that a perfect estimate of the channel h is available, the average SER for M-ary FSK can therefore be given by

$$\begin{aligned} \mathcal{P}_{M-FSK} &= \sum_{j=1}^{2} \sum_{m=1}^{M-1} p_j \frac{(-1)^m}{(m+1)} \binom{M-1}{m} \\ &\quad \times \int_0^\infty \exp\left(-\frac{m \log_2(M)}{(m+1)} \frac{E_{avg}}{N_0} \alpha_j v\right) \\ &\quad \times \frac{(1/v)}{\sqrt{2\pi\sigma_\beta^2}} \exp\left(-\frac{1}{2}\left(\frac{\ln v - \mu_\beta}{\sigma_\beta}\right)^2\right) dv. \end{aligned} \tag{18}$$

Putting $t = (\ln v - \mu_\beta)/(\sigma_\beta)$, (18) can be written as

$$\begin{aligned} \mathcal{P}_{M-FSK} &= \sum_{j=1}^{2} \sum_{m=1}^{M-1} p_j \frac{(-1)^m}{(m+1)} \binom{M-1}{m} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) \\ &\quad \times \exp\left(-\exp\left(\sigma_\beta t + \mu_\beta + \ln\left(\frac{m \log_2(M)}{(m+1)} \frac{E_{avg}}{N_0} \alpha_j\right)\right)\right) dt. \end{aligned} \tag{19}$$

The integral in (19) contains a function of the form $\exp(-\exp(x))$, and hence a closed-form solution is difficult to evaluate. This function needs to be approximated by a tractable closed-form result, and the approximation given by [15] can be used here as

$$\exp(-\exp(x)) \approx \sum_{k=1}^{K} R1_k \exp\left(-\frac{1}{2}\left(\frac{x - R2_k}{R3_k}\right)^2\right), \tag{20}$$

where $R1_k$, $R2_k$, and $R3_k$ in (20) are real constants that are tabulated in [15, Table 2]. Now, substituting (20) in (19), average SER can be expressed in approximate closed-form as

$$\begin{aligned} \mathcal{P}_{M-FSK} &\approx \sum_{j=1}^{2} \sum_{m=1}^{M-1} \sum_{k=1}^{K} R1_k p_j \frac{(-1)^m}{m+1} \\ &\quad \times \binom{M-1}{m} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) \\ &\quad \times \exp\left(-\frac{1}{2}\left(\frac{\sigma_\beta t + \mu_\beta + \ln\left(\frac{m \log_2(M)}{(m+1)} \frac{E_{avg}}{N_0} \alpha_j\right) - R2_k}{R3_k}\right)^2\right) dt \\ &= \sum_{j=1}^{2} \sum_{m=1}^{M-1} \sum_{k=1}^{K} p_j \frac{(-1)^m}{m+1} \binom{M-1}{m} A2_{j,m,k}, \end{aligned} \tag{21}$$

where

$$A2_{j,m,k} = \frac{R3_k}{\sqrt{\sigma_\beta^2 + R3_k^2}} \times \exp\left(-\frac{1}{2}\left(\frac{\mu_\beta + \ln\left(\frac{m\log_2(M)}{(m+1)}\frac{E_{avg}}{N_0}\alpha_j\right) - R2_k}{\sqrt{\sigma_\beta^2 + R3_k^2}}\right)^2\right). \tag{22}$$

It is evident from (21) that for the fixed average symbol energy, channel parameters, and noise parameters, as M increases, the average SER decreases.

3) AVERAGE ACHIEVABLE RATE OF *M*-ARY ASK

The PLC system under consideration is narrowband and has limited bandwidth; thus it is important to present a comparative analysis of the average achievable rate of M-ary ASK and M-ary FSK systems.

Let $\mathcal{C}_{M-ASK}$ represent the average achievable rate of the M-ary ASK based PLC system in bits/sec/Hz. It can be expressed as

$$\mathcal{C}_{M-ASK} = \log_2(M) \times \int_0^\infty \sum_{j=1}^{2} p_j \log_2(1 + \alpha_j(E_{avg}/N_0)v) f_\beta(v)\mathrm{d}v, \tag{23}$$

where $f_\beta(\cdot)$ and its parameters are given by (8) and (14), respectively. For high SNR (i.e., $\alpha_j(E_{avg}/N_0) \gg 1$), the average achievable rate can be expressed in approximate closed-form as [16]

$$\mathcal{C}_{M-ASK} \approx \frac{\log_2(M)}{\ln(2)}\left(2\mu_h + \ln\left(\frac{E_{avg}}{N_0}\right) + \sum_{j=1}^{2}\ln\left(\alpha_j^{p_j}\right)\right). \tag{24}$$

4) AVERAGE ACHIEVABLE RATE OF *M*-ARY FSK

Similarly, for M-ary FSK, as there are M different frequencies to send $\log_2(M)$ bits at a time, and assuming all the symbols are equally likely, the average achievable rate $\mathcal{C}_{M-FSK}$ for high SNR case can be expressed in approximate closed-form as [16]

$$\mathcal{C}_{M-FSK} \approx \frac{\log_2(M)/M}{\ln(2)}\left(2\mu_h + \ln\left(\frac{E_{avg}}{N_0}\right) + \sum_{j=1}^{2}\ln\left(\alpha_j^{p_j}\right)\right). \tag{25}$$

Since M-ary FSK uses same symbol energy for each transmission, the average symbol energy is the same as the pulse energy. Therefore, to maintain the same average symbol energy, the pulse energy of M-ary FSK must be $(M^2 - 1)/3$ times higher than that of M-ary ASK. It is also clear from the average achievable rate expressions that the bandwidth efficiency of M-ary ASK is better than that of M-ary FSK for the same average SNR.

IV. RESULTS AND DISCUSSIONS

A. FREQUENCY CONTROL USING PLC

The frequency regulation scheme using PLC proposed in this work is tested by giving a step load perturbation (SLP) to the system at 0.5 s. The increase in load leads to a reduction in system frequency measured at the control center. The change in frequency (ΔF) (p.u.) is shown in Fig. 3a. It can be seen that the controller brings the frequency back to nominal. Fig. 3a shows the frequency deviation that is used to execute secondary control at a rate of 0.01 s which means the ΔF signal is sampled every 0.01 s and the same is sent to the controller using PLC.

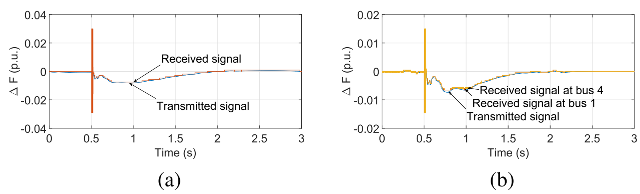

FIGURE 3. PLC performance and frequency deviation for SLP in the system. (a) Only one generator is controlling frequency. (b) Both generators are controlling frequency.

Fig. 3a shows the information signals at the transmitter and the receiver terminals. It can be observed from Fig. 3a that the transmitted and the received information signals from the PLC links are match closely. Thus, it can be concluded that the PLC system performance is satisfactory enough to be used for secondary frequency control in the smart microgrid. The minute error between the transmitted and received signal is mainly due to the quantization, and it is within acceptable limits from the frequency control point of view.

Furthermore, it can be observed from Fig. 3a that the delay between the information signals transmitted and received through the PLC link is insignificant. It is well established that substantial communication delays can lead to instability of the frequency control loops [5], [6] but in the proposed PLC based system, the delay is negligible. Therefore, it can be concluded that the stability of the microgrid is ensured while using PLC for information exchange.

B. FREQUENCY CONTROL BY MULTIPLE SOURCES

If the second generator is also a diesel engine generator with same kind of governing action as the first generator and it is also participating in frequency control, the same frequency error needs to be communicated to the second generator as well. Therefore, the frequency error transmitted at bus 10 is received at both the generator buses (bus 1 and bus 4). The error signal received at these two locations is used by both the generators for frequency regulation. The signals are shown in Fig. 3b which shows the accuracy of the received signals and there is practically no difference in the received signal at both the buses.

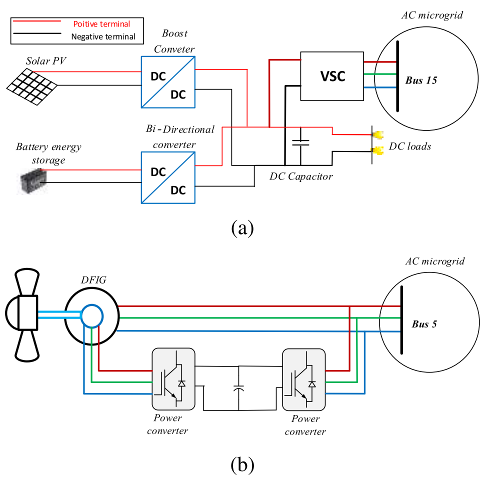

FIGURE 4. Integration of renewable energy sources with the microgrid. (a) Distributed generator based DC system interconnected at bus 15. (b) DFIG based WECS connected at bus 5.

C. FREQUENCY CONTROL IN PRESENCE OF RENEWABLE ENERGY SOURCES

The proposed PLC based frequency regulation scheme is tested in renewable energy sources (RES) based distributed generations (DGs). Most of these sources involves application of power electronic converters which have higher dynamic response. A DC system having DC sources like battery and solar photovoltaic (PV) and DC loads is connected to the AC microgrid at bus 15 as shown in Fig. 4a. Further, a doubly fed induction generator (DFIG) based wind energy conversion system (WECS) has also been connected to the microgrid at bus 5 as shown in Fig. 4b. The control methodologies used to control the various converters, to maintain maximum power point tracking and to maintain required DC link voltages are standard techniques and their discussion is beyond the scope of this paper.

The PLC performance in this scenario is tested by comparing the transmitted and received frequency error signal for a change in load at 0.5 s followed by a change in wind speed from 12 m/s to 11 m/s at 4 s. The comparison is shown in Fig. 5a. It can be seen in Fig. 5a, the received signal shows variation from the transmitted one but the absolute instantaneous error magnitude is very small and the average value is close to the transmitted signal. Moreover, the governing action is quite slow due to large time constants of mechanical systems. Thus, the high frequency error in the received signal does not initiate any governing action. Therefore, the power system performance is not deteriorated and frequency is regulated as desired. To further smoothen the received signal, a low-pass filter can be used at the output of the PLC receiver. The frequency error signal and the received signal (after filtering) is shown in Fig. 5b.

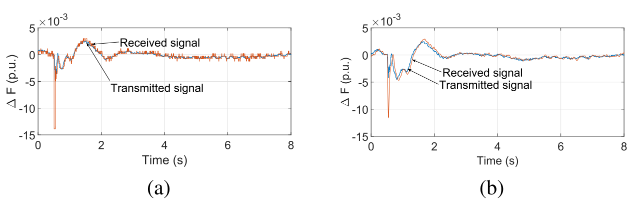

FIGURE 5. PLC performance and frequency deviation for SLP in the system having RES based DGs. (a) Transmitted and received signals. (b) Transmitted and received signals with filter at receiving end.

D. PLC: PHYSICAL LAYER

Numerical results on the performance of M-ary ASK and M-ary FSK PLC systems are presented in this subsection. For the analysis, we have considered the received average SNR without the notion of distance between the transmitter and the receiver. The fading parameter σ_h of the PLC channel depends on the PLC network selected for communication and it is often represented in dB. The value of σ_h in dB can be expressed by multiplying $(10/\ln(10))$ to the absolute value [22]. A PLC network having higher number of branches will have higher value of σ_h [11], [12]. In this analysis, a reasonable value of σ_h, which is in the range of 2 to 4 dB, is taken. The impulsive noise in PLC occurs due to switching operation in the power system, and the noise parameter p denotes the average occurrence of the impulsive noise (i.e., average switching in the power system) [14], [21], [23]. The power ratio of the impulsive noise to the background noise is denoted by η and is kept as 10; $\eta = 10$ implies that the average impulsive noise power is 10 times stronger to that of the background noise. Fitting parameters $R1_k$, $R2_k$, and $R3_k$ are calculated using curve fitting technique given in MATLAB for $K = 3$ with a root mean squared error of 8.48×10^{-3}.

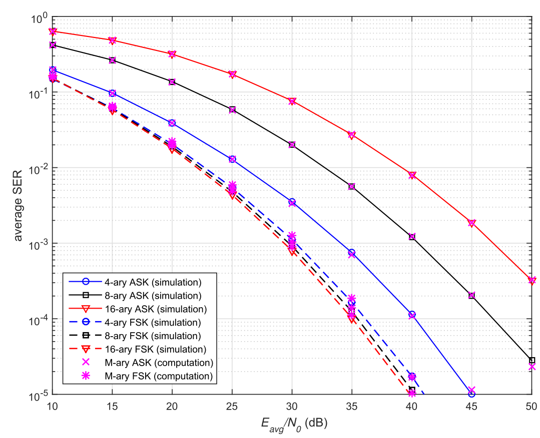

FIGURE 6. Average SER of M-ary ASK and M-ary FSK versus E_{avg}/N_0 with $\sigma_h = 3.5$ dB, $p = 10^{-1}$, and $\eta = 10$ for varying M.

1) AVERAGE SER ANALYSIS

Figs. 6 and 7 show plots of the average SER versus E_{avg}/N_0. The analytical curves for M-ary ASK and M-ary FSK are obtained using the approximate closed-form expressions (15) and (21), respectively, and are found to agree well with the simulation curves, thus validating our analysis.

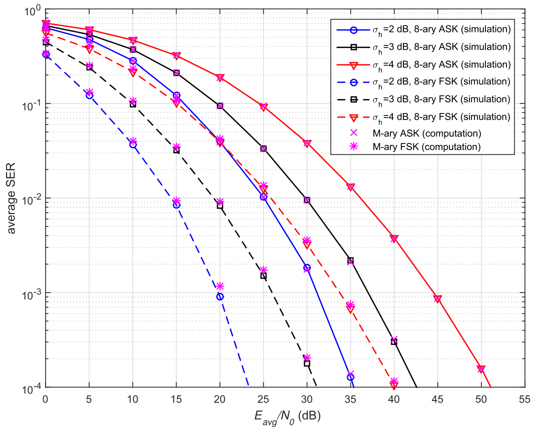

FIGURE 7. Average SER of 8-ary ASK and 8-ary FSK versus E_{avg}/N_0 with $p = 10^{-1}$ and $\eta = 10$ for varying σ_h.

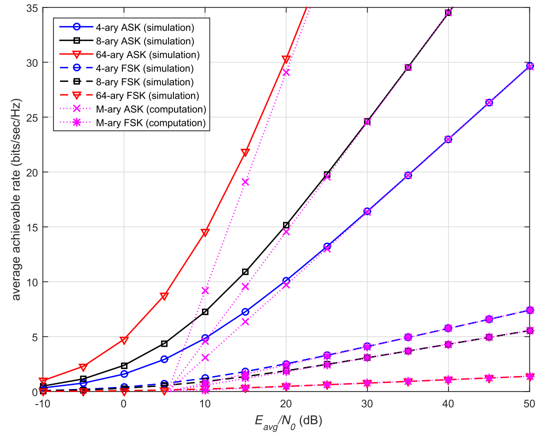

FIGURE 8. Average achievable rate of M-ary ASK and M-ary FSK versus E_{avg}/N_0 with $\sigma_h = 4$ dB, $p = 10^{-1}$, and $\eta = 10$ for varying M.

From Fig. 6, which is plotted for varying values of M with $\sigma_h = 3.5$ dB, $p = 10^{-1}$, and $\eta = 10$, a general comment that the SER performance improves with increasing E_{avg}/N_0 for both the modulation schemes, can be made. Next, we observe that in the case of fixed E_{avg}/N_0, as M increases, the SER performance of M-ary ASK degrades, whereas it improves for M-ary FSK. However, with increase in M, the SER performance degradation of M-ary ASK is quite significant when compared with the SER performance improvement of M-ary FSK. For example, when changing from $M = 4$ to 16 at an SER of 10^{-3}, the E_{avg}/N_0 improvement of M-ary FSK is $\approx$ 1 dB whereas, the E_{avg}/N_0 degradation of M-ary ASK is $\approx$ 12 dB. Hence, it can be concluded that, for fixed E_{avg}/N_0, with increase in M, the SER performance of M-ary ASK deteriorates at a rate that is much faster than the rate of SER performance improvement of M-ary FSK.

Fig. 7 is plotted for varying values of σ_h with $M = 8$, $p = 10^{-1}$, and $\eta = 10$. It can be observed that for all the values of σ_h, the SER performance improves with increasing E_{avg}/N_0 for both the modulation schemes. Furthermore, we observe that in the case of fixed E_{avg}/N_0, the SER performance of both the modulation schemes degrades with increase in σ_h. This means that, as the number of branches and loads connected to the PLC network increases (which causes σ_h to increase), the SER performance degrades. Furthermore, from Fig. 7, it can be numerically observed that to achieve an SER of 10^{-3} with $\sigma_h = 4$ dB, 8-ary FSK requires E_{avg}/N_0 to be 26 dB, whereas this requirement is 37 dB for 8-ary ASK. Therefore, it can be concluded that to achieve the same SER performance for a fixed σ_h, M-ary FSK requires less average symbol energy than M-ary ASK.

Further, to verify the performance of the PLC system obtained from above mentioned analysis, we have introduced log-normal gain and Bernoulli-Gaussian noise into the simulink model. Thereafter, we recorded the transmitted and received signals and calculated the average SER for SNR=35 dB, $M = 64$, $p = 0.1$, and $\eta = 10$ with two different values of σ_h. The received signal is the same as in Fig. 3. For $\sigma_h = 3$ dB, the average SER from simulink is measured to be 0.166 and 0.17 from (15). Similarly, for $\sigma_h = 1$ dB, the average SER from simulink is recorded as 0.044 and 0.047 from (15). It is assumed that the channel is perfectly known at the receiver; that can be achieved using pilot symbols.

2) AVERAGE ACHIEVABLE RATE ANALYSIS

Fig. 8 shows plots of the average achievable rate versus E_{avg}/N_0 for varying M. The analytical curves for M-ary ASK and M-ary FSK are obtained using the approximate closed-form expressions (24) and (25), respectively, and are found to agree well with the simulation curves at high E_{avg}/N_0, thus validating our analysis. In this Fig. the average achievable rate plots for varying values of M with $\sigma_h = 4$ dB, $p = 10^{-1}$, and $\eta = 10$ are plotted. General observation shows that the average achievable rate performance for both the modulation schemes improves with the increase in E_{avg}/N_0 value for all M. Further, we observe that in the case of fixed E_{avg}/N_0 as M increases for M-ary ASK, the average achievable rate performance improves whereas, for M-ary FSK, the performance degrades. Further, it is to be noticed that with an increase in M, the improvement in the average achievable rate performance of M-ary ASK is significant and the degradation in the average achievable rate performance of M-ary FSK is nominal. For example, when moving from $M = 4$ to 64 at $E_{avg}/N_0 = 20$ dB, the average achievable rate improvement for M-ary ASK is $\approx$ 20 bits/sec/Hz whereas, achievable rate degradation for M-ary FSK is $\approx$ 2.4 bits/sec/Hz and almost reaching to zero. As a result, M-ary ASK is a better choice for PLC than M-ary FSK.

V. DISCUSSION

From smart grid perspective, both RF and PLC appear to be suitable options. However, PLC offers many advantages over RF communication as listed below:

1) PLC offers a better appliance-to-appliance connectivity

that suits a smart grid environment as all data acquisition and control nodes are often connected to the power line [10].

2) Wireless technology may see many folds increase in traffic because of IoT applications in near future that inturn would result in increased latency [24]. However, PLC will remain an option for smart grid application.
3) Wireless systems use antenna for radiating electromagnetic waves and these waves travel in all directions in case of omni-directional antenna and in specific direction in case of directive-antenna, whereas in PLC, signal propagates along the power line. Thus, using omni directional antennas cause wastage of energy and directional antennas needs to be placed in proper direction each time the placement of transmitter receiver changes [25].
4) Wireless systems have a drawback of shadowing that occurs sometimes in underground and metallically covered areas that reduces the coverage area for an RF based system [25].

VI. CONCLUSION

This work emphasizes on the use of PLC as a viable communication solution for frequency regulation in a smart microgrid since it is a retrofit technology. The frequency error sensed at any point in the microgrid system is shown to be successfully transferred to the generating unit located at a different position using an M-ary ASK based PLC system. After that, the received signal is used to regulate the mechanical power generated by the diesel engine to regulate the frequency of the microgrid at the generating unit. Although there is a minimal mismatch in the transmitted and the received information signals due to the quantization process and the additive noise, the desired frequency regulation is shown to be achieved. Hence, it can be concluded that the performance of PLC for information exchange is acceptable in such applications. Furthermore, a comparative analysis of M-ary ASK and M-ary FSK based PLC systems is also presented. The PLC channel coefficients and the additive impulsive noise samples are derived from a log-normal distribution and a Bernoulli-Gaussian process, respectively, and approximate closed-form expressions for the average SER and the average achievable rate are derived for both the PLC systems. From the observations mentioned above and the fact that narrowband PLC has limited bandwidth and supports signal transmission at comparatively high SNR, it can be concluded that M-ary ASK is a better choice for signaling in PLC than M-ary FSK.

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