Performance Analysis of Micro Wind Turbine Based Energy Systems with Series Connected Inverters and a Novel Switching Network

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Abstract

The increase in demand for electricity coupled with the obligation to use sustainable technologies, has led to research and development in small and medium scale renewable source based electricity generation systems. When it comes to the smaller systems, one of the important criteria in commissioning/ operating is simplicity of the system apart from the systems capability to produce power with acceptable standards. To meet this requirement, a novel switching network referred in this paper as comparator based switching signal selection (CSSS) network, has been proposed for controlling the inverter circuit in the generation system. The network enables the use of any two level inverter modulation schemes to control any levels of series connected inverter. This eliminates the complexity like generation of multiple carrier waveforms, performing complex calculations to generate switching signals. To demonstrate the effectiveness of employing this switching network in a generation system, the performance of a micro wind turbine based energy system has been analyzed using parameters like harmonic distortion of current, voltage and k-factor of the transformer. A comparative study of these parameters has also been performed to understand how comparable the performance of CSSS

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network is to the existing modulating schemes. The result of analysis and comparison shows that by employing a CSSS network, not only satisfactory performance can be obtained from the system, but also the control algorithm can be simplified.

Keywords: Micro wind turbines, Series connected inverter, Performance analysis of inverter, k-Factor, Multicarrier pwm, CSSS network.

1 Introduction

The demand supply gap for electric energy has led to wide spread research and developments in technologies involving all types of electric energy sources. The moral obligation to opt for non-pollutant sources have created more interest among the researchers to look towards renewable energy sources. Part of the total electrical energy demand can be met by extracting energy from wind using wind energy systems. Even though the energy generated by these micro and small wind energy systems seems to very less to satisfy the enormous needs, they do provide a solution for the power demand problem. Especially to power up rural homes and to make buildings go greener by integrating wind turbines in built in environment. Energy problems which are considered local may be addressed by using this technology of extracting power from wind using micro and small wind turbines [2]. In every such electricity generation systems, a power modulator controlled by a suitable modulation strategy is employed in addition to the wind turbine and generators [7]. This reported work deals with the analysis of performance of micro wind turbine based energy systems with series connected inverters controlled by a novel modulation strategy which is both simple and effective.

2 Overview of the Micro Wind Turbine Energy System (MWES)

Micro wind turbine energy systems are typically well suited for built-in environment [1]. An electricity generation system using micro wind turbines consists of a wind power conversion mechanism, necessary power electronic converters and a system controller. The wind power conversion mechanism consists of micro wind turbines which are coupled to electric generators usually made of permanent magnet synchronous type because of their high power density and reliability [2]. Since the permanent magnet synchronous generators in these MWES are of smaller ratings, the voltage generated by them usually is in the range of 45V to 90V. In order to drive a load rated for 230V (single phase) or 440V (three phase), it is essential to connect these micro wind turbine generators in series-parallel combination to meet the load requirement. The voltage generated by the micro wind turbine generators are processed using appropriate power converters. The ideal choice in this situation is to use series connected inverters along with ac–dc rectifiers on the source side [8]. A typical layout of such an arrangement is shown in Figure 1.

Naturally, when an electricity generation system is selected to power up the loads in a consumer premises, the system had to meet certain requirements. The primary requirement will be to control the inverter according to the load requirement and adhere to the power quality requirements [3]. Wide varieties of inverter topologies have been suggested for use in MWES [3–7]. Also a suitable modulation strategy is to be adopted to generate switching (gate) signals to control the inverter switches. The modulation strategy should enable the inverter to produce a voltage which is sinusoidal in nature and should also keep track of the changes in the system parameters while generating switching signals. A number of modulation strategies are available to control inverters [9–12]. When compared to the modulation techniques of conventional two level inverters, the techniques available for controlling series connected inverters are complex. It is observed that this complexity increases when the number of inverter levels increases. For a small and medium scaled generation systems, this complexity may be a deterrent factor in implementing such systems. To overcome this disadvantage, a novel switching network (called CSSS network) is proposed. The network makes use of a simple comparator logic and a multiplexing logic to distribute the gate signals generated by conventional modulation schemes to the different switches of a series connected inverter.

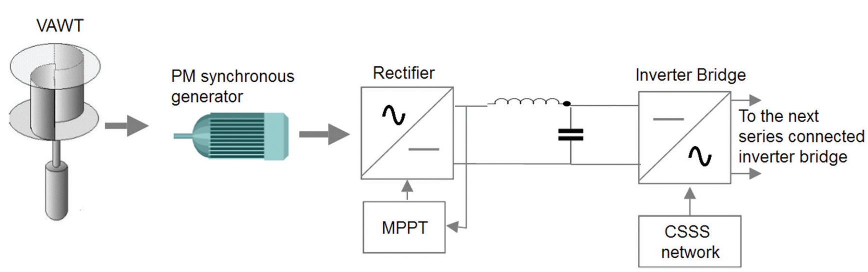

Figure 1 One of the inverter units with VAWT and PMSM in MWES Layout.

Through this reported work, it has been demonstrated that the complexity of the inverter control can be reduced without compromising the performance of the inverter.

3 Overview of Comparator Based Switching Signal Selection Network

The key for obtaining satisfactory performance from any type of inverter is the modulation technique used rather than the topology used. A handful of techniques are available for controlling series connected inverters [3, 12]. But as stated previously, the complexity of these techniques increases as the number of inverter levels increases. The CSSS network offers a simple solution to use any of the available two level inverter modulation techniques to control a series connected inverter with literally any number of levels [13].

Basically, the CSSS network uses the magnitude of the modulating signal to route appropriate switching signals to the semiconductor switches in a series connected inverter. In its simplest form, the network consists of a comparator which compares the magnitude of the modulating signal (V_{ref}) with predefined threshold values. The result of comparison is used to decide whether to send a PWM signal or Logic HIGH/LOW signal to the gate terminal of the power switch in each inverter, as illustrated in Figure 3(a).

For instance, a five-level series connected inverter shown in Figure 2(a), requires two sets of switching signals for driving the two h-bridge inverters (upper and lower h-bridges). Any of the two level modulating techniques can be chosen to generate the pulse width modulated switching signals. The CSSS network constantly monitors the magnitude of the modulating signal. Based on the comparison of the modulator's magnitude with the threshold values (in this case $V_{ref}/2$), appropriate switching signals are sent to the semiconductor switches.

During the positive cycle ($0 < \omega t < \pi$) of the modulating signal shown in Figure 2(b), the switching signal generation network shown in Figure 3(a) functions in the following manner:

i. Driving lower bridge inverter switches (S5,S6): The PWM switching signals are channeled to drive the inverter switch S5 for the time duration when the instantaneous value of the modulating signal is less than the threshold limit ($V_{ref}/2$) as shown if Figure 3(b). The threshold value is half the peak value of the reference in this case. As long as the condition in (1) is satisfied, the inverter switch S5 receives the PWM switching signals.

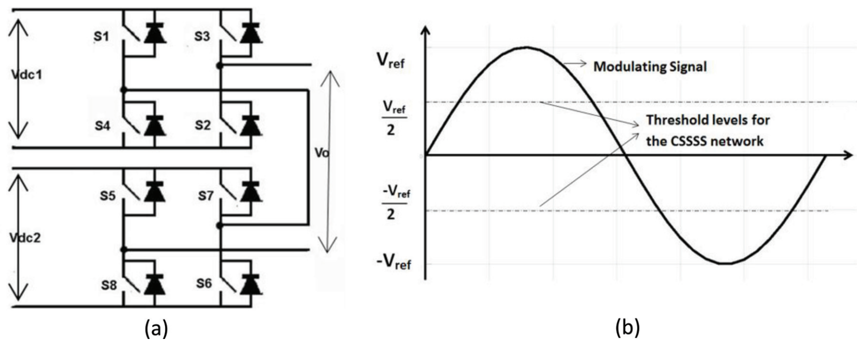

Figure 2 (a) A 5-level inverter, (b) Modulating wave and threshold level for a CSSSN in a 5-level inverter.

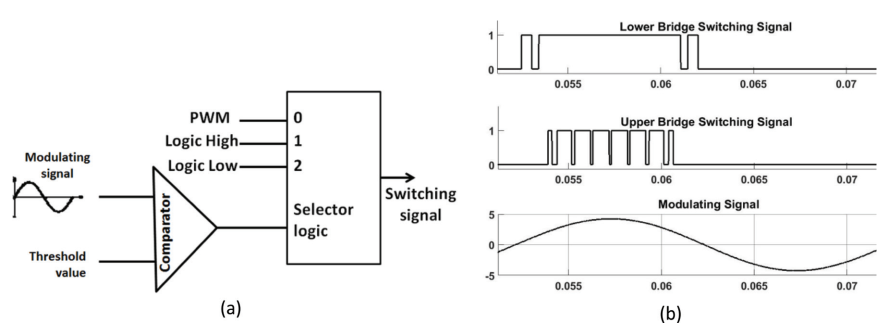

Figure 3 Comparator based Switching Signal Selection (CSSS) network (a) Logic, (b) Switching signals generated by the CSSS network (during postive half cycle).

$$0 < \mathrm{V_{ref(i)}} < \mathrm{V_{ref(p)}}/2 \tag{1}$$

where $\mathrm{V_{ref(i)}}$ is the instantaneous value of the modulating signal and $\mathrm{V_{ref(p)}}$ is the peak value of the modulating signal. Beyond this time duration, logic high signal is applied to switch S5 until the condition becomes TRUE again, during the rest of the positive cycle. Switch S6 is kept continuously on during the entire positive cycle.

ii. Driving upper bridge inverter switches (S1, S2): In this case, the PWM switching signals are channeled to drive the switch S1 for a time duration when the condition in (2) is satisfied.

$$\mathrm{V_{ref(p)}}/2 < \mathrm{V_{ref(i)}} < \mathrm{V_{ref(p)}} \tag{2}$$

Switch S1 is turned off for the rest of the time duration during the positive and negative half cycle of the reference signal. Switch S2 is kept on continuously during the entire positive cycle.

The number of threshold values (N_T) required can be determined using the relation $N_T = L - 3$ (where L is the number of levels in inverter output). In this case, for a five level inverter two threshold values are required ($N_T = 5 - 3 = 2$. i.e. $+V_{ref}/2$ and $-V_{ref}/2$). Every additional inverter unit in the series connected inverter will require two additional comparators along with the two additional threshold values.

The discussed method can be extended to produce switching signals for any levels of inverters. By setting up appropriate number of comparator threshold limits, the modulating signal (in this case, SPWM signals) can be channeled to different inverter bridges at appropriate instances. Based upon the procedure discussed in this section, a generalized algorithm has been described below for implementing the concept using stored program computers.

For time duration of ($0 < \omega t < \pi/2$):

Step-1: Read L (number of output levels of the inverter)
Step-2: Compute n = (L − 1)/2
Step-3: Compute x = n − 1
Step-4: For j = 0 : 1 : x

i. Read instantaneous value of the reference signal $V_{ref(i)}$
ii. If [$(V_{ref(p)}/n)*j) < V_{ref}(i) < (V_{ref(p)}/n)*(j+1)$]
    a. then apply the modulated gate switching signals to inverter bridge ‘j’ (lower most bridge is bridge ‘0’)
    b. wait until [$V_{ref(i)} < ((V_{ref(p)}/n)*(j+1))$]

Step-5: When an upper bridge is fed with switching signals, appropriate switches of all lower bridges are kept continuously ON.

The CSSS network which is described in this section has been used to control the series connected inverter in the micro wind turbine energy system. The performance of MWES with series connected inverter and the proposed modulation strategy is analyzed in the next section.

4 Performance Analysis of the MWES with CSSS Network

In order to understand the effect of employing the CSSS network in a micro wind turbine energy system, a simulation study of the system with different kinds of modulation schemes (with and without the CSSS network) has been performed. The performance of the system is analyzed by observing performance parameters like the output voltage, output current, the total harmonic distortion of current and voltage waveforms, individual harmonic components of the output voltage and current waveforms. The results and the analysis are presented in this section.

The system which was simulated consists of a vertical axis wind turbines of 1kW for every inverter level on the source side. The wind speed was assumed constant throughout the study. A reactive (inductive) element with inductive reactance of $X_L = 0.5R$ (where R is the resistive component of load) was used as a load to the system. A 5-level and a 7-level, three phase series connected inverter configuration was used for the performance study. The modulation schemes selected for controlling the series connected inverter include the proposed CSSS network with a simple SPWM scheme and the conventional multicarrier modulation scheme (including phase disposition, phase opposition disposition and alternate phase opposition disposition). Various test cases were considered with variation of amplitude modulation index and frequency modulation index. The amplitude modulation index was varied from 0.7 to 1.3 and frequency modulation index was varied from 10 to 360. A simple test script was used to run the simulation for all cases listed above and to record the values during each test run.

For a 5-level inverter, the plot of the voltage THD with respect to amplitude modulation index (m_a) and frequency modulation index (m_f) is shown in Figure 4. On observing the linearly fitted line in the plot, it can be noted that the inverter with CSSS network is producing voltage THD which is fairly

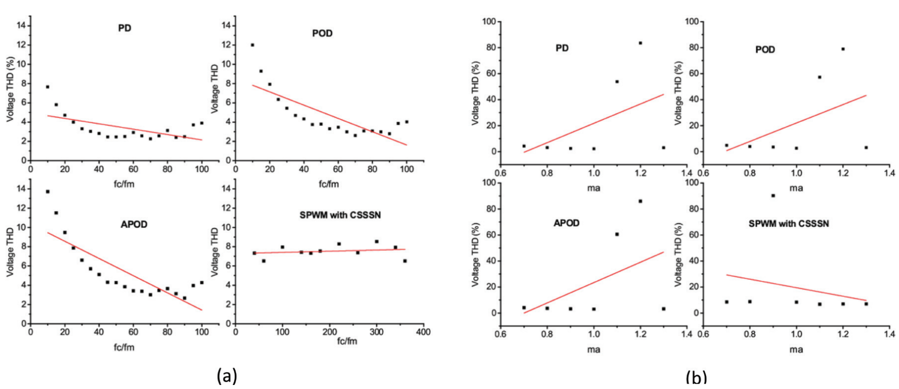

Figure 4 Variation of voltage THD with variation of (a) f_c/f_m, (b) m_a, for 5-level inverter.

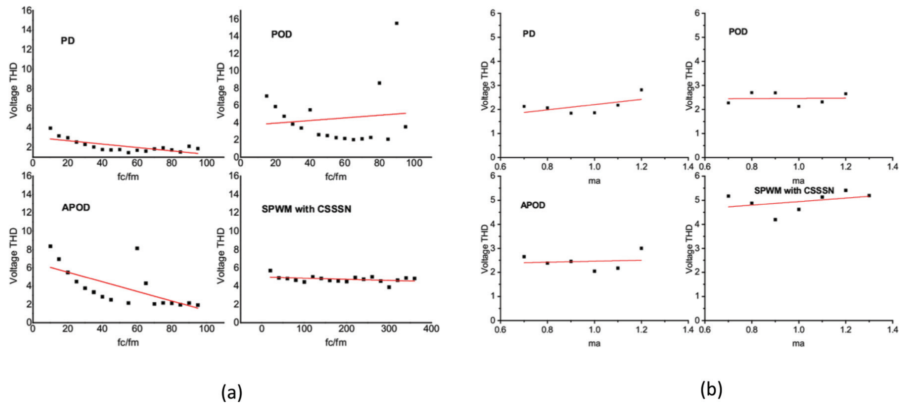

Figure 5 Variation of voltage THD with variation of (a) f_c/f_m, (b) m_a, for 7-level inverter.

constant throughout all operating conditions. When using other modulation schemes, the voltage THD comparatively varies over a wider range. Similar kind of results of voltage THD is obtained for a 7-level inverter, which is given in Figure 5.

The plot of current THD with respect to amplitude modulation index and frequency modulation index for 5-level inverter and 7-level inverter configurations is shown in Figure 6 and Figure 7, respectively. Similar to the voltage THD plots, it can be observed that the inverter with CSSS network gives a performance (in terms of current THD) which is almost stable over the entire operating region. Also, the current THD values obtained from a CSSS network is comparable to the values obtained using other modulation schemes. On comparing the linearly fitted line in Figure 4(a), it can be noted that the output current distortion is less and the current THD values are almost constant under different inverter switching frequencies. A similar kind of stable performance is obtained when the amplitude modulation index is varied. It is evident from the plot of Figure 6(b) that the inverter with CSSS network provides stable performance in both over-modulated and under-modulated regions unlike other modulation schemes where the performance is not satisfactory in over-modulation region.

Apart from the THD components, the impact of these modulation schemes on the k-factor of the transformer is also analyzed. K-factor usually gives the information about how much a distribution transformer needs to be de-rated at the time of installation. As micro wind turbine energy systems usually forms a part of distributed generation, where electricity is generated locally and

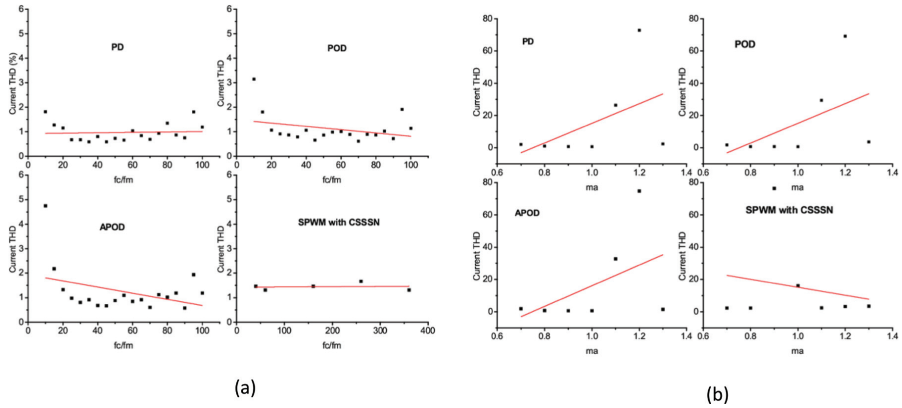

Figure 6 Variation of current THD with variation of (a) f_c/f_m (b) m_a, for 5-level inverter.

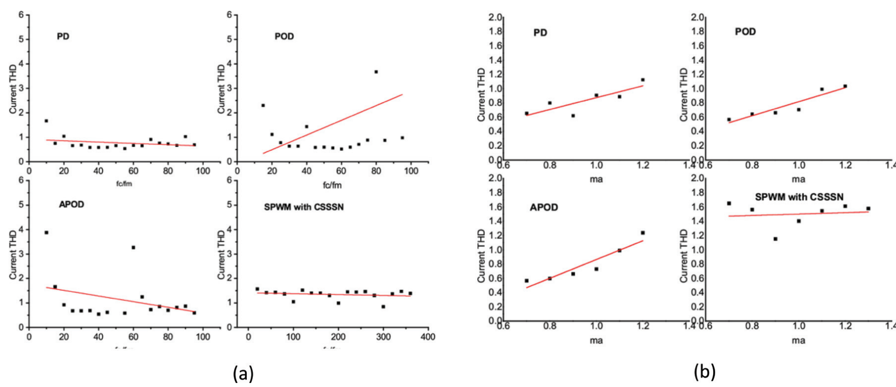

Figure 7 Variation of current THD with variation of (a) f_c/f_m (b) m_a, for 7-level inverter.

distributed to the local distribution network it is essential to study the impact of the modulation schemes on the k-factor of the transformer also. The k-factor in this case is calculated using the relation,

$$\text{k-factor} = \frac{i_1^2\left(1^2\right) + i_2^2\left(2^2\right) + i_3^2\left(3^2\right) + i_4^2\left(4^2\right) + \ldots + i_n^2\left(n^2\right)}{i_1^2 + i_2^2 + i_3^2 + i_4^2 + \cdots + i_n^2} \tag{3}$$

where $i_1, i_2, i_3 \ldots i_{\mathrm{n}}$ are the load current at the respective harmonics expressed in per unit basis.

The variation of k-factor for a 5-level and 7-level inverter configurations when amplitude modulation index and frequency modulation index is varied has been presented in Figure 8 and Figure 9.

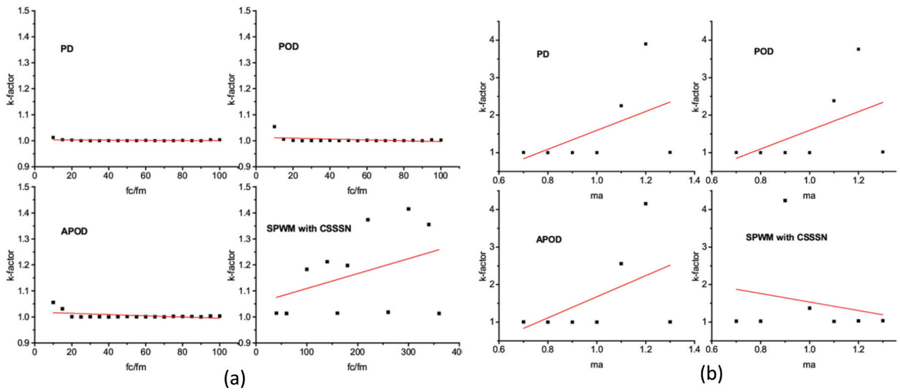

Figure 8 Variation of k-factor with variation of (a) f_c/f_m, (b) m_a for 5-level inverter

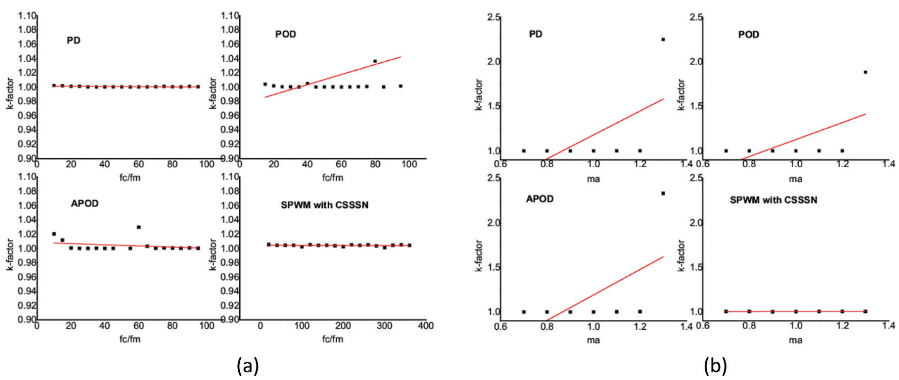

Figure 9 Variation of k-factor with variation of (a) f_c/f_m, (b) m_a for 7-level inverter.

The load in the simulation study is a reactive load and its impedance value is held constant for all operating conditions. As a result of that, the k-factor is just above the value of 1 in all the cases. In practical cases, when non-linear loads like switching converter based loads are connected to the lines, the k-factor may further increase. Since the objective of this work is to prove that the proposed switching network can give comparable satisfactory performance to other modulation schemes, other types of non-linear loads are not used for simulation. In fact, it can be observed that the k-factor is stably maintained in a very low range by using the CSSS network when compared to other modulation schemes.

The results have been tabulated for the purpose of getting a clear picture of the performance of the MWES under various test conditions. Table 1 shows the range of values for Voltage THD, Current THD and k-factor when the frequency modulation index (f_c/f_m) is varied. It can be observed that the when the proposed CSSS network is used to control the inverter, the performance remains almost constant for a range of input conditions. Table 2 shows the range of values for Voltage THD, Current THD and k-factor when

Table 1 Effect of variation of f_c/f_m on performance parameters under different modulation schemes

Performance Parameters	Modulation Scheme / Test Cases	PD	POD	APOD	Proposed Scheme with CSSSN
V_{THD}	5-level	3–5	2.5–7.5	2–9	7.5–8
	7–level	3–1.5	4–5	2–6	4.5–5
I_{THD}	5–level	0.5–1.5	0.5–1.5	0.5–2	∼1.5
	7–level	0.5–1	0.5–2	0.5–1.5	1–1.5
K–factor	5–level	∼1	∼1	∼1	1.3
	7–level	∼1	0.95–1.05	∼1	∼1

Table 2 Effect of variation of m_a on performance parameters under different modulation schemes

Performance Parameters	Modulation Scheme / Test cases	PD	POD	APOD	Proposed Scheme with CSSSN	
V_{THD} (in %)	5-level	Under-modulation	∼5	∼5	∼5	∼10
		Over modulation	20–40	20 – 40	20 – 40	∼10
	7-level	Under-modulation	2	2.5	2.5	∼5
		Over modulation	2–3	2–3	2–3	∼5
I_{THD} (in %)	5-level	Under-modulation	∼4	∼4	∼4	∼7
		Over modulation	4–30	4–30	4–30	∼5
	7-level	Under-modulation	0–1	0.5–0.75	0.5–0.75	∼1.6
		Over modulation	1–1.5	0.75–1	0.75–1.5	∼1.6

(*Continued*)

Table 2 Continued

Performance Parameters	Modulation Scheme / Test cases	PD	POD	APOD	Proposed Scheme with CSSSN	
k-factor	5-level	Under-modulation	∼1	∼1	∼1	∼1
		Over modulation	1–2.5	1–2.5	1–2.5	∼1
	7-level	Under-modulation	∼1	∼1	∼1	∼1
		Over modulation	1–1.5	1–1.5	1–1.5	∼1

the amplitude modulation index (m_a) is varied. Two important conclusions can be derived from the results tabulated in Table 2. First, the performance of the inverter using the proposed CSSS network is comparable to the existing modulation techniques, when the modulation index is less than 1 (i.e. under-modulation region). Second, the performance is better and remains uniform under various test conditions, when the modulation index is more than 1 (i.e over-modulation region).

5 Conclusion

A novel switching network has been proposed in this paper to control the series connected inverters in a micro wind turbine based energy systems. Since simplicity is one of the key deciding factors for installation and operation of small generation systems, the switching networks is designed to have a simple structure and to provide easiness in operation. The performance of the system using this switching network has been analyzed under different operating conditions and was found to be satisfactory. The results obtained indicates that the system using a CSSS network can provide a stable satisfactory performance under varying input conditions, which is desirable for any system. A comparative study with other modulation schemes has also been performed to demonstrate that the performance of the proposed network is comparable to other schemes In fact, under certain operating conditions, the performance of the system with the proposed network is better than the other modulation schemes. The CSSS network also offers the flexibility to easily control any levels of series connected inverter, making this a potential technique for widespread application in series connected inverter control.

References

[1] Li, D., Wang, S., and Yuan, P. (2010). A review of micro wind turbines in the built environment. In *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific,* 1–4. IEEE.

[2] Liang, W., and Liu, W. (2010). Key technologies analysis of small scale non-grid-connected wind turbines: A review. In *World Non-Grid-Connected Wind Power and Energy Conference (WNWEC),* 1–6. IEEE.

[3] Colak, I., Kabalci, E., and Bayindir, R. (2011). Review of multilevel voltage source inverter topologies and control schemes. *Energy Conversion and Manage.* 52, 1114–1128.

[4] Chub, A., Husev, O., Blinov, A., and Vinnikov, D. (2017). Novel Isolated Power Conditioning Unit for Micro Wind Turbine Applications. *IEEE Transactions on Industrial Electronics*. 64, 5984–5993.

[5] Babaei, E., Alilu, S., and Laali, S. (2014). A new general topology for cascaded multilevel inverters with reduced number of components based on developed H-bridge. *IEEE Transactions on Industrial Electronics*, 61, 3932–3939.

[6] Malinowski, M., Gopakumar, K., Rodriguez, J., and Perez, M. A. (2010). A survey on cascaded multilevel inverters. *IEEE Transactions on Industrial Electronics*, 57, 2197–2206.

[7] Pathmanathan, M., Tang, C., Soong, W. L., and Ertugrul, N. (2008). Comparison of power converters for small-scale wind turbine operation. In *Power Engineering Conference, AUPEC'08.* Australasian Universities, 1–6. IEEE.

[8] Melício, R., Mendes, V. M. F., and Catalão, J. P. S. (2008). Two-level and multilevel converters for wind energy systems: a comparative study. In *Power Electronics and Motion Control Conference, EPE-PEMC 2008,* IEEE, 1682–1687.

[9] Deng, F., Liu, D., Chen, Z., and Su, P. (2017). Control strategy of wind turbine based on permanent magnet synchronous generator and energy storage for stand-alone systems. *Chinese Journal of Electrical Engineering* 3, 51–62.

[10] Ding, K., Cheng, K. W. E., and Zou, Y. P. (2012). Analysis of an asymmetric modulation method for cascaded multilevel inverters. *IET Power Electronics* 5, 74–85.

[11] Wang, H., Nayar, C., Su, J., and Ding, M. (2011). Control and interfacing of a grid-connected small-scale wind turbine generator. *IEEE Transactions on Energy Conversion* 26, 428–434.

[12] McGrath, B. P., and Holmes, D. G. (2002). Multicarrier PWM strategies for multilevel inverters. *IEEE Transactions on Industrial Electronics*, 49.
[13] Kodeeswara kumaran, G., and Parthiban, P. (2016). 'Application of Delta Modulation Strategy to Series Connected Inverters' in *Proceedings of the IEEE International Conference on Circuits, Control, Communication and Computing (I4C2016)*, Bangalore, India, 280–283.

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