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PERFORMANCE IMPROVEMENT IN MICRO WIND ENERGY SYSTEMS WITH CASCADED INVERTERS USING A NOVEL SWITCHING NETWORK

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Abstract:

Electricity generation using technologies involving renewable energy sources have gained momentum in the wake of increased concern on environmental impacts and dwindling fossil reserves. Extraction of wind energy through small and micro wind turbines is an attractive option for distributed generation in isolated regions and standalone green buildings. One of the issues faced in a micro wind energy system (MWES) with multilevel inverters is the unequal voltage source condition which at times decreases the output power delivered to the load and also increases the harmonic contents. A novel switching signal generation logic has been suggested to control the cascaded inverters with unequal dc sources and to improve the output power delivered. This switching network also enables the use of any two level inverter modulation schemes to control any levels of cascaded inverters. To demonstrate the effectiveness of this logic, a micro wind energy system with vertical axis wind turbines and cascaded inverters has been modeled, simulated and the results were analyzed. The incorporation of the proposed switching logic to control the cascaded inverter with unequal voltage sources improves the rms value of output current and voltage, and increases the power delivering capability by around 20%. In addition to increased power delivery, the switching network is capable of maintaining the harmonic contents to satisfactory levels.

I. INTRODUCTION:

The demand for electricity is steadily rising as humans depend more and more on electrical equipment in their everyday life. The world energy council sees world electricity consumption increasing to more than 40,000 TWh/Year in 2040 [1]. Any attempt to increase the generating capacity through conventional power stations will only aggravate the existing environmental problems. A conservative estimate reveals that in order to generate 1kWh of electrical energy from the conventional thermal power plants, 0.8 kg of CO2 is being released in to the atmosphere [2]. The profound impact of these conventional power stations on the environment is a matter of grave concern. The solution to the energy demand issue should therefore be viable, both environmentally and economically.

Among the various technologies existing for generating electricity, in theory and practice, technologies involving renewable sources look quite promising. Meeting the future energy demand from renewable energy sources, would therefore be the viable solution. Energy from wind being one of the cleanest forms of energy can be used to meet part of the total electrical energy demand. The prospect of installing small wind turbines provides additional scope of using wind power to augment the existing generation capacity. Though the amount of energy generated by the small and micro wind turbine systems seems to be comparatively less to satisfy the enormous needs, they do provide a part of the solution to the power demand issues.

Generating electrical energy from micro and small wind turbines can be an extremely advantages feature when it comes to rural electrification, developing greener buildings or even deploying distributed generation plant with option to export power to the main grid [3]. Most energy demands which are considered local may be addressed by using this technology of extracting power from wind using micro and small wind turbines. The fact that there is considerable amount of potential to be exploited in low speed winds coupled with the fact that installation of large wind turbines is not always feasible in all areas, highlights the option to use micro and small vertical axis wind turbines to augment the electrical energy production. Wind turbine based energy systems owing to its negligible carbon footprint have been deployed in places wherever possible.

II. MICRO WIND ENERGY SYSTEMS:

The Micro Wind Energy Systems (MWES) are mostly targeted to be used in standalone applications in areas where wind speed is considerably low. The suggested system configuration for these systems is shown in Fig. 1 and consists of micro wind turbines, PMSM generators, power converters, system controller and safety.

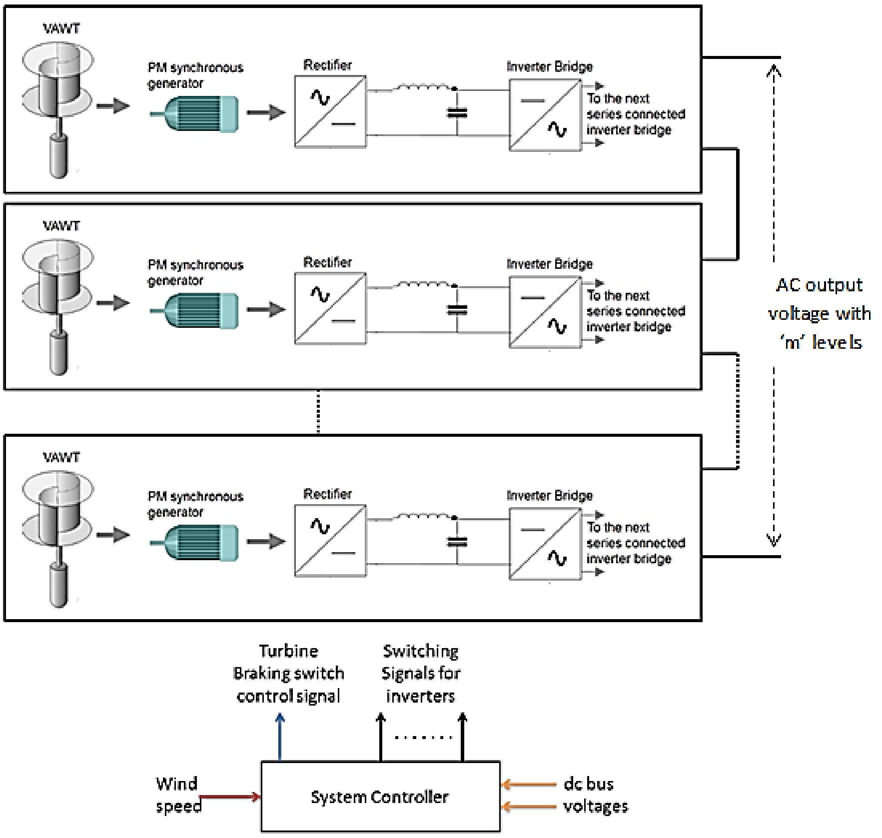


Figure 1. Micro Wind Energy System

As vertical axis turbines performs better than a horizontal axis turbines in low wind speed regions, vertical axis microwind turbines are employed in the suggested MWES configuration. Research at Caltech has shown that a carefully designed wind farm using vertical axis wind turbines (VAWT) can have an output power ten times that of horizontal axis wind turbines (HAWT) of the same size [4]. The PMSM generators coupled to the microwind turbines produce power with voltages lesser than the standard magnitudes. So after rectification, the magnitude of generated voltage is increased by connecting the rectifier outputs in series using a cascaded H-bridge inverter. When compared to other configurations with step-up transformer or boost converter, deployment of a cascaded multilevel inverter (MLI) is a better option due the several reasons ranging from improved power quality to reduction of cost involved in reactive elements used for boosting the output voltage.

For a wind turbine, the maximum power that can be possibly extracted, at a wind velocity 'v', is given by Betz's law [5] as,

$$P_{max} = \frac{16}{27}\left(\frac{1}{2}\rho r h v^3\right) \quad \square\square\square$$

where h and r are the height and radius of the rotor. However, under practical conditions, the extractable power is just half of the value. From the energy conversion equation (1), it can be seen that the output power of the wind turbine is sensitive to wind speed. This implies that the terminal voltage of the generators will not be constant due to the varying nature of wind. It can't be assumed that variation of wind speed will affect the output of all the micro wind turbines in the same way. Each micro wind turbine generator may act as a voltage source of different magnitude. This leads to a situation where the dc link voltages in each H-bridge of the cascaded multilevel inverter to be different. The cascaded MLI with different dc link voltages (i.e. unequal dc sources) is often referred to as asymmetrical cascaded inverter[6]. The unequal voltage condition of different sources affects the rms value of the output voltage of the series connected inverter. In addition to change in the rms value, output wave-shape changes and thereby the harmonic profile of the output waveform is also altered. Under these circumstances, the modulation technique used to control the cascaded inverter has to perform the task of improving the rms value and keep the distortion to the minimum.

The output voltage produced by asymmetrical cascaded inverter can be expressed using the transcendental equation (2).

$$V(\omega t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\left(V_1\cos(n\theta_1) + V_2\cos(n\theta_2) + \cdots + V_S\cos(n\theta_S)\right)\sin(n\omega t) \quad (2)$$

where S is the number of dc sources and V_1, V_2,….V_S are the voltage magnitude of the individual sources of each inverter in per unit. Few modulation techniques exploit equation (2) to computer switching angles, through complex computations, to control the inverter [7,8,9]. Few other multilevel inverter modulation techniques uses multiple carrier (level shifted or phase shifted) to control the inverter [10]. The complexity of these modulation techniques increases with unequal sources in MWES. A much simpler method has been proposed in this paper to handle the inverters with unequal voltage sources. The proposed method, referred as extended Comparator based Switching Signal generation Network, helps improve the rms value at all unequal source conditions. A simple method have been reported by the authors [10] to generate switching signals of multilevel inverter with equal voltage sources which is referred as Comparator based Switching Signal generation Network.

III. CONTROL OF CASCADED INVERTER IN MWES;

A. Extemded Comparator based Switching Signal generation Network:

The operating principle of the extended CSSS network is explained in the following situations using a five level inverter as example.

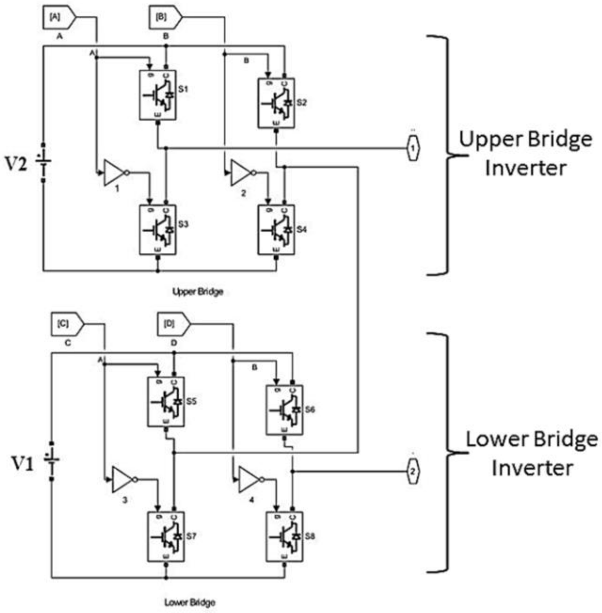


Figure 2 A 5- level cascaded inverter

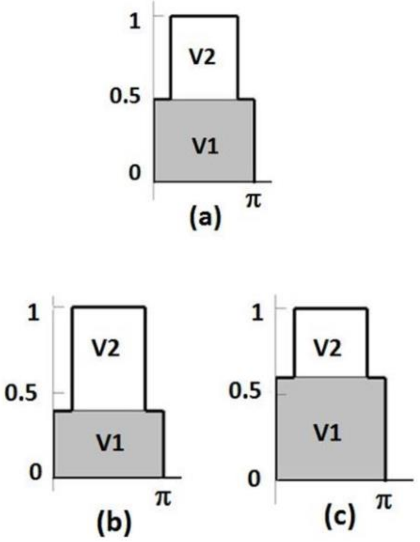


Figure 3 Five level inverter output under (a) equal source condition (b) unequal source condition, $V_1 < V_2$ (c) unequal source, $V_1 > V_2$

Fig. 2 shows a five level inverter and Fig. 3 shows the inverter output under equal source condition and un-equal source conditions. Let the area covered by the waveforms in Fig. 3(a), (b) and (c) be A_1, A_2 and A_3, respectively. Referring to the five level series connected inverter in Fig. 2, it can be said that the shaded area of the waveforms in Fig. 2 is formed due to lower bridge inverter source voltage V_1. The un-shaded area is formed due to the upper bridge inverter source voltage V_2. The area of these waveforms can be generally expressed as in (3).

$$A = \{area\ formed\ by\ V_1\} + \{area\ formed\ by\ V_2\} \qquad (3)$$

$$= \{V_1 \pi\} + \{V_2 \left(\frac{5\pi}{6} - \frac{\pi}{6}\right)\}$$

where 5π/6 and π/6 are the instances at which the upper bridge inverter gets turned ON and OFF.

The area of the waveform in Fig. 2(a) (when the sources are having equal magnitude) can be expressed as in (4).

$$A_1 = V_1 \pi + V_2 \left(\frac{5\pi}{6} - \frac{\pi}{6}\right) \qquad (4)$$

$$= V_1 \left\{\pi + \left(\frac{5\pi}{6} - \frac{\pi}{6}\right)\right\}, when\ V_1 = V_2$$

When the sources have un-equal magnitude as shown in Fig. 2(b) and Fig. 2(c), the two source voltages are related using the expression$V_2 = xV_1$ (where x is the scaling factor). The area of these waveforms, under various un-equal source conditions, are expressed as in (5) and (6),

$$A_2 = V_1\left\{\pi + x\left(\frac{5\pi}{6} - \frac{\pi}{6}\right)\right\}, when\ V_1 > V_2\ and\ x < 1 \qquad (5)$$

and

$$A_3 = V_1\left\{\pi + x\left(\frac{5\pi}{6} - \frac{\pi}{6}\right)\right\}, when\ V_1 < V_2\ and\ x > 1 \qquad (6)$$

It can be inferred from the above calculations that the rms value of the output waveform can be improved significantly if the positions of the lower and upper bridges are interchanged during un-equal voltage conditions (when V_1 is less than V_2). By interchanging the bridges and thereby interchanging the source positions, the source with higher voltage magnitude contributes to more power delivered to the load. Thus interchange of sources, when required, results in significant increase in the rms value of the output waveforms.

For example,

When V_1=0.5 p.u, V_2=0.5 p.u (i.e. V_1= V_2 and x=1), the area of A_1 is calculated using (4) as, A_1=2.61

When V_1=0.6 p.u, V_2=0.4 p.u (i.e. V_1> V_2 and x<1), the area of A_2 is calculated using (4) as, A_2=2.72

When V_1=0.4 p.u, V_2=0.6 p.u (i.e. V_1 < V_2 and x>1), the area of A_3 is calculated using (4) as, A_3=2.51

It can be inferred from the above calculations that the rms value of the output waveform can be improved significantly if the positions of the lower and upper bridges are interchanged during un-equal voltage conditions (when V_1 is less than V_2). By interchanging the bridges and thereby interchanging the source positions, the source with higher voltage magnitude contributes to more power delivered to the load. Thus interchange of sources, when required, results in significant increase in the rms value of the output waveforms.

The operation of the extended CSSS network is decided based on this inference and conclusion. As physical interchange of the bridges during the operation of the MWES is not possible, the switching signals used to control each inverter bridges can be interchanged to

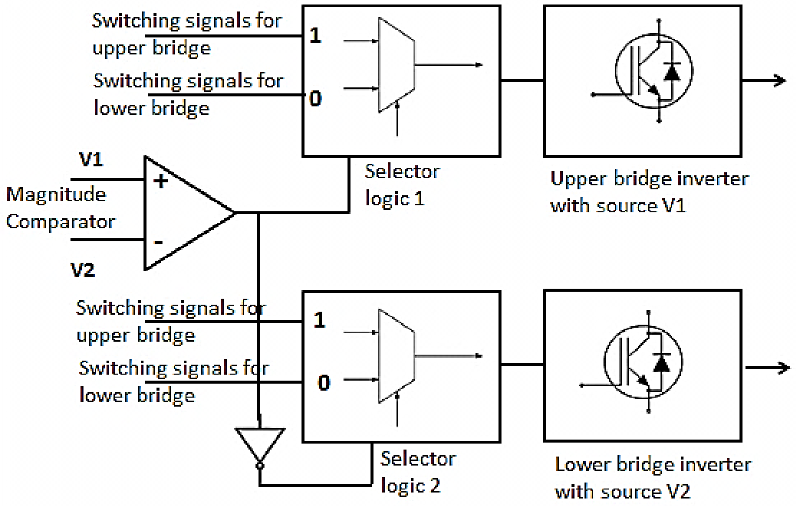


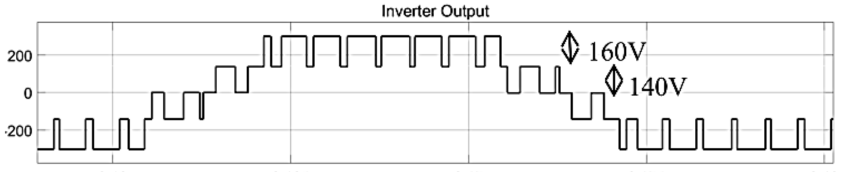
Figure 4 Logic diagram for Extended-CSSS network in the MWES to handle unequal sources conditions

logically interchange the bridge positions (when $V_1 < V_2$). The extended CSSSN monitors the magnitude of each inverter's input source voltage and the position of the individual inverter bridges is changed logically, if required, to improve the rms value of the output. The logic of extended CSSS network is shown in Fig. 4, which is intended for use in MWES to improve the output rms during unequal source conditions. As mentioned earlier, the lower bridge inverter's input voltage is referred as $V_1$and upper bridge voltage as V_2. A comparator compares the magnitude of V_1 and V_2, and controls the functioning of the selector logic. Whenever $V_1 < V_2$ (i.e. upper bridge inverter has a source magnitude greater than lower bridge inverter source magnitude), switching signals originally meant for controlling upper bridge inverter is given to lower bridge inverter and vice versa.

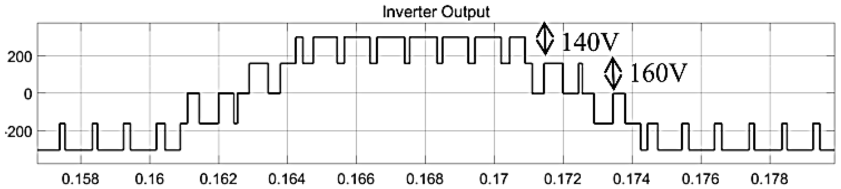
B. Simulation of MWES with extended CSSSN technique;

In order to demonstrate the effectiveness of the extended CSSSN technique, a Micro Wind Energy System with a 5-level cascaded inverter with 1kW VAWT on each h-bridge inverter was simulated. A reactive load with $X_L = 0.5R$ was used as a load to the inverter. The cascaded inverter of the MWES was controlled using various multicarrier modulation techniques and extended CSSSN technique. The multicarrier modulation techniques used for analysis include Phase Disposition (PD), Phase Opposition Disposition (POD) and Alternate Phase Opposition Disposition (APOD). Sinusoidal Pulse Width Modulation (SPWM) technique is used to generate the two level switching signals which are then distributed to the cascaded inverters using the extended CSSS network.

The inverter output voltage waveforms for unequal source condition (when lower bridge inverter source has less voltage magnitude compared to higher bridge inverter source. $V_1=0.87V_2$ (i.e. $V_1=140V$, $V_2=160V$) with extended CSSSN logic is shown in Fig. 5.



(a)



(b)

Figure 5 Five-level cascaded inverter output when V1=140V and V2=160V (a) without extended-CSSSN (b) with extended-CSSSN

Output waveforms in Fig. 5(a) and Fig. 5(b) were obtained at the output of the MWES when the cascaded inverters were controlled without and with extended CSSSN technique. It can be noted from the inverter output waveform in Fig. 5(b) that the extended-CSSS networks has logically altered the inverter positions when $V_1=140V$ and $V_2=160V$. The inverter h-bridge with 160V source is operated (as lower h-bridge) to produce the lower portion of the waveform and the inverter with 140V source is operated (as upper h-bridge) to produce the upper portion of the waveform, thus increasing the rms value of the output waveforms.

Different test cases were used to analyze the performance of MWES which includes conditions related to under modulation and over modulation (with amplitude modulation index ma varying from 0.7 to 1.3). The plot of variation of Vrms and Irms over amplitude modulation index is shown in Fig. 6. Under unequal voltage source condition (when $V_1 < V_2$), it can be observed from Fig. 6(a) that the rms value of output voltage waveform of cascaded inverter using extended CSSSN technique is significantly improved (almost by 30%) when compared to output voltage waveforms of the inverter using multicarrier modulation techniques. In addition to the increase in voltage rms, the current rms in Fig. 6(b) has also significantly increased by over 20% when extended CSSSN technique was used to control the cascaded inverter in the micro wind energy system. This significant increase in voltage rms and current rms will lead to more power being delivered to the load, thus improving the overall system efficiency.

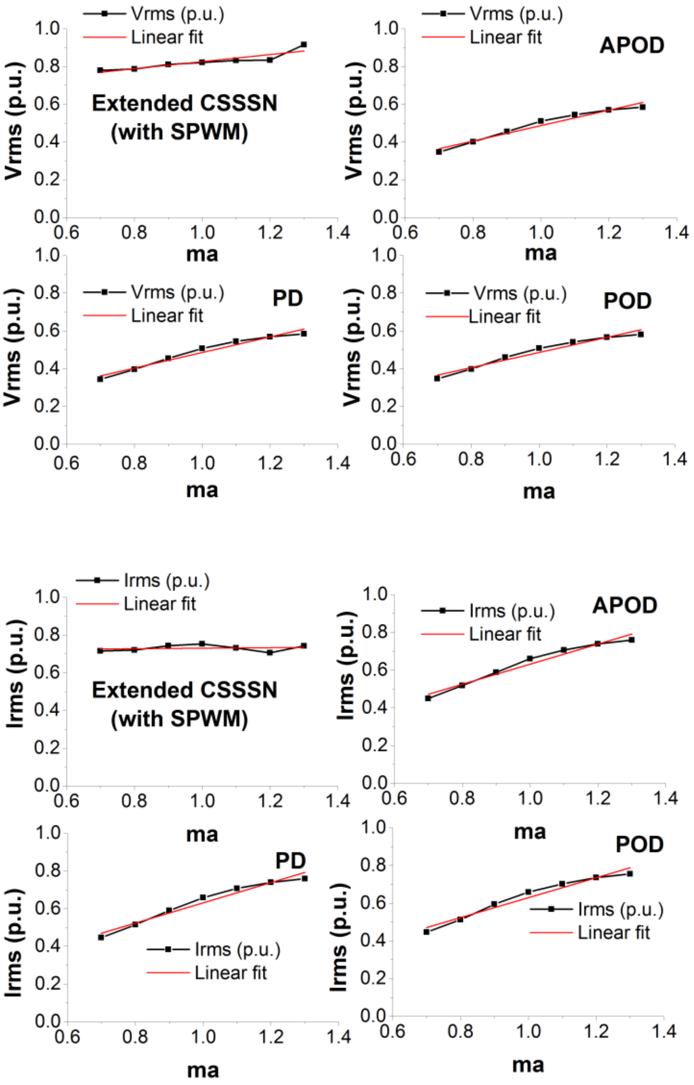


Figure 6 Comparison of MWES inverter performance with unequal sources ($V_1 < 0.8V_2$) under different modulation techniques (a) Variation of voltage rms w.r.t varying amplitude modulation index, ma (b) Variation of current rms w.r.t varying ma

The effect on the harmonic content of the output waveforms due to the inclusion of extended CSSSN was also analyzed. The plot of variation of total harmonic distortion (THD) of voltage and current waveforms is shown in Fig. 7. It can be observed from Figure 7(a) that in spite of the source voltages being unequal (i.e. $V_1 < V_2$), the voltage THD values obtained for different amplitude indexes, when extended CSSSN is used, are comparable to the cases when multicarrier modulation schemes are used. Moreover it can be observed that the voltage THD values remains fairly constant during under modulation and over modulation, whereas the voltage THD values are higher in under modulation regions and comparatively lesser in over modulation regions when multicarrier schemes are used.

On a closer look at Fig. 7(b), it can be observed that the current THD values of the output waveform are fairly constant when extended CSSSN is used and is comparable to that of the other modulation schemes.

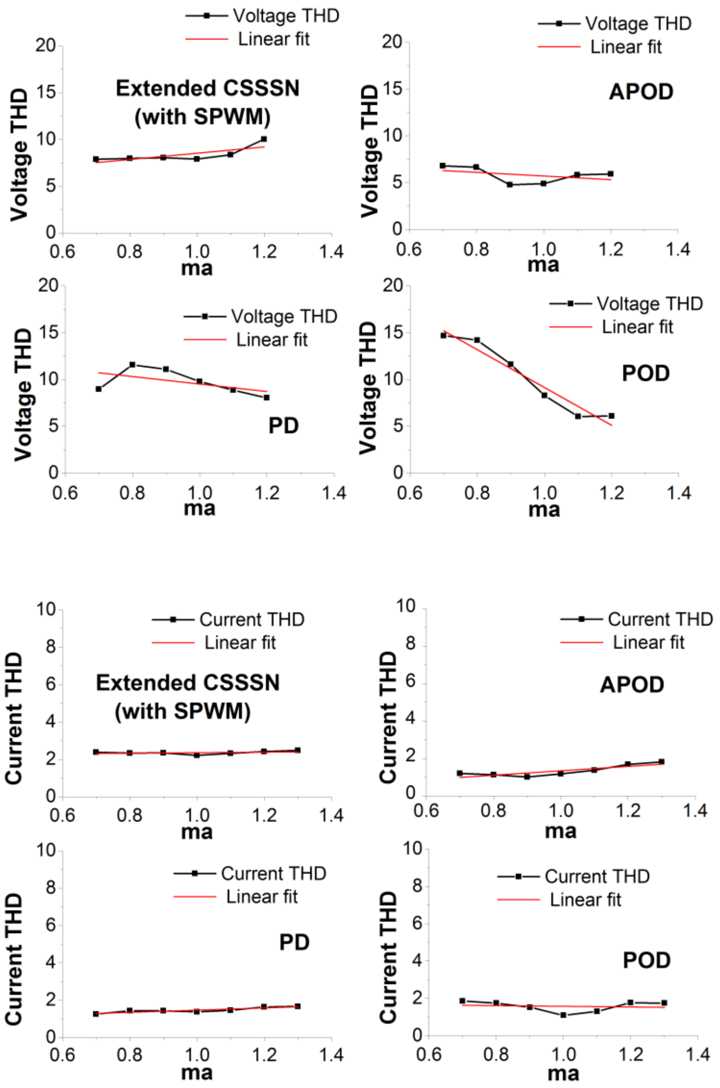


Figure 7 Comparison of MWES inverter performance with unequal sources ($V_1 < 0.8V_2$) under different modulation techniques (a) Variation of voltage THD w.r.t varying amplitude modulation index, ma (b) Variation of current THD w.r.t varying ma

The analysis of the results indicates that the obtained results are in-line with the analytical conclusion derived earlier. The rms values of the MWES output current and voltage are improved when the extended CSSS network's functionality is used.

IV. CONCLUSION :

For a micro wind energy system where wind is the primary input energy source, the modulation strategy employed should control the inverters in such a way that the system should deliver as much power as possible to the load during varying wind conditions. A configuration of MWES with vertical axis wind turbines and cascaded inverters controlled by a novel yet simple switching signal generation technique is presented in this paper. The analysis of simulation results indicate that the output power delivered to the load can be improved under all unequal source conditions and at the same time the distortion of the output waveforms can be kept minimum using the extended comparator based switching signal generation technique.

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