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RESEARCH ARTICLE

Hybrid AC and DC power distribution

S. Jayawardena[1], P. Binduhewa[2] and J.B. Ekanayake[2,*]

[1]*Sri Lanka Railways, Ratmalana, Sri Lanka*
[2]*Department of Electrical and Electronic Engineering, University of Peradeniya, Peradeniya, Sri Lanka*

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Abstract: Interest in the use of DC for medium and low voltage distribution circuits is growing as a means of reducing the multiple power conversion stages associated with connecting renewable energy sources and DC powered consumer electronic devices to the existing AC system.

The possibility of carrying AC power and injected DC power at the distribution transformer in the same distribution line and filtering out them separately to AC and DC loads were investigated. Both simulations and laboratory experiments were used to prove this concept of hybrid distribution. A comparative study was carried out to show that the proposed hybrid solution minimises the energy losses in power conversion stages when integrating renewables.

Keywords: DC distribution, power converters, energy efficiency.

INTRODUCTION

The first ever electrical distribution is using DC by Thomas Alva Edison in 1882 in Pearl Street, New York. However, due to inability of boosting DC voltage at different stages, the world electrical distribution shifted to AC. This was triggered by the invention of the transformer by Nikola Tesla in 1897. Since then the electrical distribution was carried out mainly by AC.

The interest for the use of DC for power transmission at high voltage levels has gained momentum since 1954. Power transfer by High Voltage Direct Current (HVDC) is used to connect asynchronous AC systems and for circuits of underground or submarine high voltage cables longer than about 50 km (depending on the voltage) (Andersen, B.R. *et.al*., 2000, Kirby N. M. *et.al*., 2002). HVDC is also considered for the connection of large wind farms far offshore (Kirby, N. M. *et.al*., 2002, Asplund, G. *et.al*., 1998). Further, HVDC becomes an attractive alternative to AC transmission when length of the overhead line exceeds about 600 km.

Even though DC high voltage transmission is now well established, the use of DC at Medium Voltage (MV), i.e. 1~30kV and Low Voltage (LV), i.e. <~1kV, levels is very limited. However, interest in the use of DC for MV and LV distribution circuits is growing for the following reasons:

- Photovoltaic (PV) panels produce a DC output voltage and before being connected to an AC grid the DC output must be converted to AC. Further, modern wind turbines employ two converters (AC to DC and DC to AC) with a DC bus in between. When connecting renewable energy sources to the existing AC system through multiple power conversion stages, there will be increasing complexity and reduced efficiency. Instead, if the renewable energy sources are directly connected to DC networks the power loss in converters can be eliminated thus saving 2.5% to 10% of the energy transferred (Zhang, W. *et.al*., 2012).

- Many distributed generation systems, Micro-grids and energy storage devices use power electronic interfaces to the AC grid. These sources are compatible with DC distribution systems where the energy can be used directly to supply loads and/or energy storage devices. This results in reduced conversion losses (Hammerstrome, D. J., 2007).

- To provide reliability against unplanned AC outrages, uninterruptible power supplies (UPS), which are essentially battery storage systems with a DC bus, are employed. Furthermore, Electric Vehicles (EVs) are not only significant consumers of electrical

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**Corresponding Author's Email*: jbe@ee.pdn.ac.lk

power, but their batteries could also provide improved grid reliability and energy storage whenever they are grid-connected. The conversion stages associated with these distributed energy storage devices are reduced if they are used with a DC network.

- With the unprecedented development of electronic technology, DC powered consumer electronic devices such as computers, televisions and cordless tools have become a significant part of the system load. For example in a typical home, except the washing machine and fridge/freezer all the other appliances/components are DC-internal or native-DC loads. Most of these appliances when connected to the AC system employ Switch Mode Power Supplies (SMPSs).Efficiency of these SMPSsare rather low and is in the range of 30 – 40% for external converters like those used in laptop computers and 65-70% of internal converters. If these appliances are fed with DC, a DC to DC converter is required in some application to match the DC bus voltage with the internal voltage of the appliance. The efficiency of a DC to DC converter is rather high and is in the range of 85-95%. As the energy consumption of consumer electronic equipment increases, supplying energy through the traditional AC system will become less efficient and more complex, because more of the energy must be converted to DC.

- Overall energy efficiency can be enhanced when in addition to a low-voltage AC network, buildings and homes also have a low-voltage DC supply. In the future, homes will have heat-pumps, photovoltaic systems and charging points for Electric Vehicles. All these devices use power electronic converters with filters to connect to the AC grid. Major cost savings can be realized by avoiding the complex converter systems.

Different concepts for distribution of electricity through DC at MV and LV levels and their comparison with AC system is reported in the literature.Salonen, P. *et.al*. (2008) discusses a number of different connection topologies of LVDC distribution system and the way loads can be connected to them. In order to utilise all three wires of the existing LV distribution system a ±750 V bipolar DC distribution is considered and protection required for safety is discussed. A loss comparison between AC vs DC distribution is reported in (Starke, M. *et.al*., 2008). Even though the exact benefits of DC distribution depends on the system voltage used and the proportion of AC to DC loads, thisarticle shows that for similar maximum voltage levels ($\sqrt{2}$ times rms for AC) and AC loads to DC loads proportion of 50% to 50%, the DC incur low losses compared to AC. A comparison of DC distribution over AC for MV applications are presented in (Korytowski, M., 2011). A comparison of the performance of the MVDC system over MVAC system is presented under steady state operation and under different faults. Even though DC distribution is considered as a preferred option considering the benefits such as higher power capacity for a given cable size, enhanced reliability, low losses and voltage quality improvement (Salonen, P. *et.al*., 2008), the most of the configurations proposed in the literature demand considerable changes to the existing infrastructure and more complex arrangements.

Considering the fact that existing loads such as motors are AC driven and many other loads such as entertainment and IT equipment are DC driven, in this paper a hybrid distribution approach is proposed. Even though a hybrid approach is presented in (Pasonen, R., 2014), it requires five wires for distribution of AC and DC separately. Only the neutral wire is utilised by both systems. In Basu, K.P. *et.al*.(2005) and Gopi, C.*et.al*. (2016), the feasibility of converting a double circuit AC line into composite AC-DC power transmission is demonstrated. Here, DC power is obtained through a 12-pulse Rectifier Bridge used in HVDC and injected to the neutral point of the secondary of sending end transformer and inverted at the receiving end. Three conductors of the second line provide return path for the DC current. Zigzag connected winding is used at both ends to avoid saturation of transformer due to DC. The simultaneous AC-DC transmission has been investigated in Choudhary,V.*et.al*. (2011)using PSCAD/EMTDC simulations to study its feasibility for a double circuit line.The schemes presented in (Basu, K.P.*et.al*., 2005,Choudhary,V.*et.al*., 2011) are mainly for transmission applications, and needs two three winding transformers of Star-Zigzag-Delta and four converter bridged on both sending and receiving ends. This arrangement will not be technically or economically attractive for the distribution end of the power system. Therefore in this paper a scheme which can be introduced to distribution circuits with minimum changes to the existing scheme is proposed.

AC AND HYBRID DISTRIBUTION OF PV

PV power distribution using AC: Existing scheme

In existing applications, a PV array is connected to the AC system through an inverter. Commonly used topologies are: strings connected in parallel to a central inverter, strings connected through multiple inverters, and individual modules connected through micro-inverters. The connection of a PV array into a central inverter is shown in Figure 1. In the figure central inverter operating on PWM is utilised. The voltage is then boost to 33 kV and connected to the 33 kV distribution busbar.

Hybrid PV power distribution – Proposed scheme

Figure 2 shows a hybrid scheme in which output DC from the PV array is send through the distribution line as a train of pulses. This scheme needs a three winding transformer at the consumer end.

The different components in Figure 2 are described below:

a) Injection transformer

This is a three-phase distribution transformer of which the primary is delta-connected. As shown in Figure 3, the secondary is connected as star. The pulse output of the single phase H-bridge is connected between the star point and the ground. The phase voltages are given by:

$$v_a = v_{pulse}(t) + V_m \sin \omega t \tag{1}$$

$$v_b = v_{pulse}(t) + V_m \sin(\omega t - 2\pi/3) \tag{2}$$

$$v_c = v_{pulse}(t) + V_m \sin(\omega t - 4\pi/3) \tag{3}$$

where $v_{pulse}(t)$ is the pulse waveform injected to the neutral and V_m is the maximum value of AC voltage.

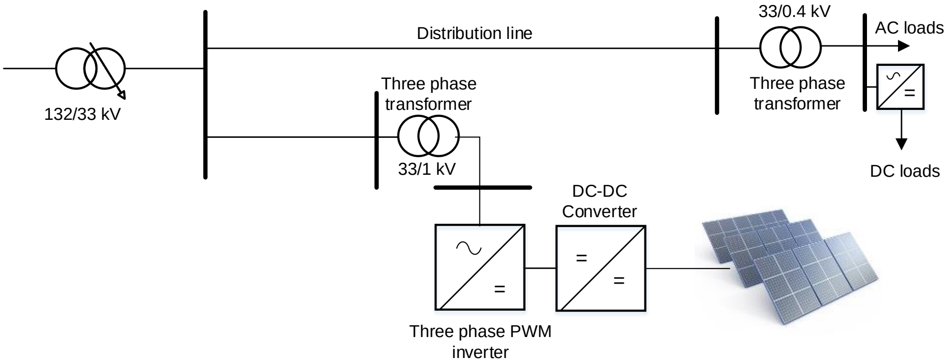


Figure 1: Connection of a large PV array to the distribution network through an AC connection.

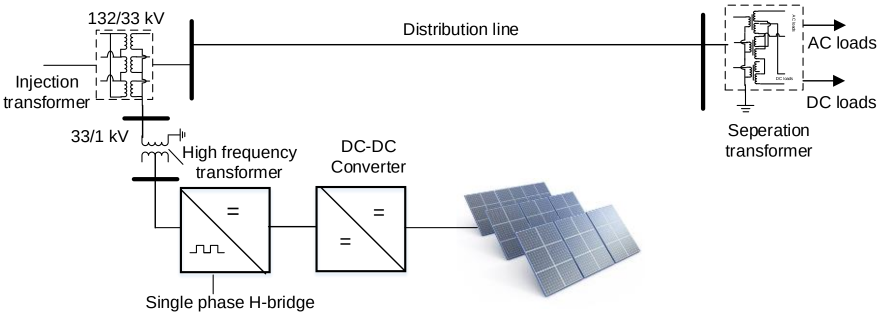


Figure 2: Proposed connection of a large PV array to the distribution network.

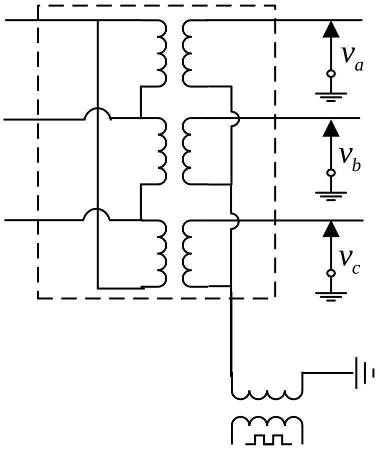


Figure 3: Injection transformer.

b) Separation transformer

This is a three-phase, three-winding transformer of which the primary is star-grounded. Secondary windings are connected in such a way that the difference between two output phase voltages makes the AC voltage of one phase (shown in Figure 4) and similarly the other two phases. The injected pulse voltage is obtained by connecting all the tertiary windings in series. In order to minimise losses associated with the high frequency pulse passes through this transformer, core should be designed with low-loss magnetic material.

Therefore, the waveform of the extracted AC voltage of one phase in the secondary side of the separation transformer is given by:

$$\begin{aligned} v_{ab} &= k'[v_{pulse}(t) + V_m \sin \omega t] \\ &\quad - k'[v_{pulse}(t) + V_m \sin(\omega t - 2\pi/3)] \\ &= \sqrt{3k' V_m \sin(\omega t - 2\pi/6)} \end{aligned} \tag{4}$$

where *k'* is the turns ratio between primary and secondary

Similarly the three-phase system is formed by v_{bc} and v_{ca} (only v_{ab} is shown in Figure 4)

The waveform of output pulse voltage from the series connected tertiaries of the separation transformer is given by:

$$\begin{aligned} v_{ab} &= k''[v_{pulse}(t) + V_m \sin \omega t] \\ &\quad + k'[v_{pulse}(t) + V_m \sin(\omega t - 2\pi/3)] \\ &\quad + k'[v_{pulse}(t) + V_m \sin(\omega t - 4\pi/3) \\ &= 3k'' v_{pulse}(t) \end{aligned} \tag{5}$$

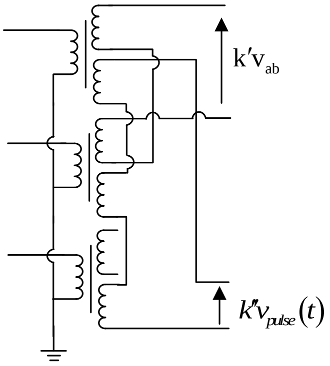


Figure 4: Separation transformer.

c) Single phase H-bridge

Figure 5 shows the H-bridge circuit. When two Insulated Gate Bipolar Transistors (IGBT), S_1 and S_4 are ON and two IGBTs, S_3 and S_2 are OFF. The voltages across A and B (V_{AB}) hasa positive voltage corresponding to the output of the PV array. Once the states of switches are inverted, the terminal voltage becomes the negative of the PV output voltage. In this application the ON/OFF time of each pair of switches was set to be 50% of the switching period thus to obtain 0.5 duty cycle pulse waveform.

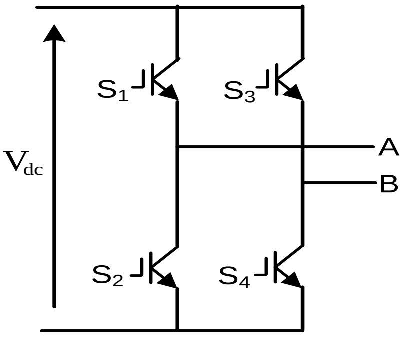


Figure 5: H-bridge.

Comparison of the AC and Hybrid distribution

In this comparison it was assumed that the PV panels associated with two systems shown in Figures 1 and 2 are identical. The following assumptions were made:

Rated voltage of the PV panel V_{PV}

Rated power of the PV panel P_{PV}

Grid side phase voltage (secondary of the transformer) V_{Grid}

Modulation index of PWM $m_a = 0.9$

PWM and pulse converter is operating at the unity power factor

Three phase PWM converter is shown in Figure 6.

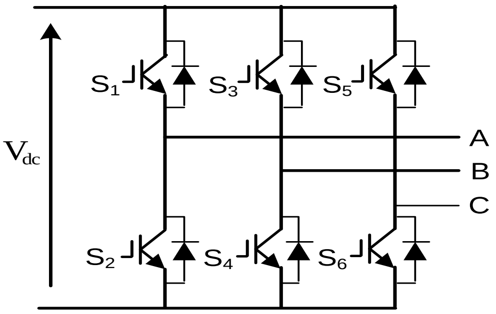


Figure 6: Three phase converter.

The relationship between grid side voltage and V_{dc} is given by

$$V_{Grid} = 0.353 m_a \tag{6}$$

Assuming at the rated conditions, the duty ratio of the DC-DC converter is d_1

$$V_{dc} = d_1 V_{PV} \tag{7}$$

Figure 7 shows the voltage and current waveforms for PWM switching. It was assumed that the mid-point of the dc link is connected to the neutral of the input transformer. Therefore the voltage rating of the IGBTs is given by

$$\text{Voltage rating} = V_{dc} = d_1 V_{PV} = \frac{V_{Grid}}{0.353 m_a} \tag{8}$$

Assuming that the efficiency of the DC-DC converter is η_{DC} and that of the converter is η_{VSC}

$$3 V_{Grid} I_{Grid} = P_{PV} \times \eta_{DC} \eta_{Pulse} \tag{9}$$

where I_{Grid} is the rms value of the ac current shown in Figure 2

Therefore the current rating of the switch is given by

$$\text{Current rating} = 0.33 \frac{P_{PV} \times \eta_{DC} \eta_{Pulse}}{V_{Grid}} \tag{10}$$

Assuming that the IGBT and its anti-parallel diode has the same ON state voltage drop, V_{ON}, the conduction losses were calculated approximately as:

$$\text{Conduction losses} = 3 \times I_{Grid} \times V_{ON} \tag{11}$$

If the PWM frequency is f_{PWM}, switching losses are approximately given by $3 V_{dc} I_{Grid} f_{PWM}$.

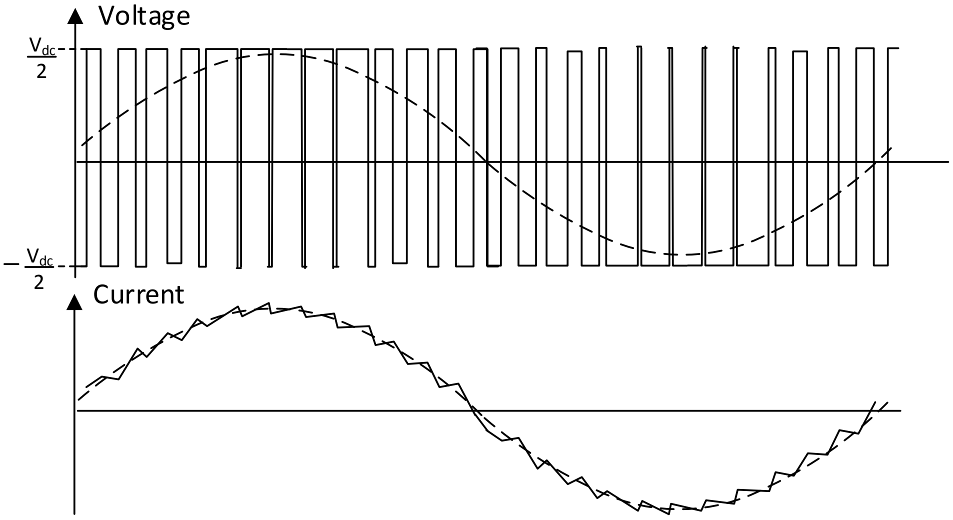


Figure 7: Current and voltage for PWM switching.

For the H-bridge converter shown in Figure 5, the relationship between grid side voltage and V_{dc} is given by

$$V_{Grid} = V_{dc} \tag{12}$$

Assuming at the rated conditions, the duty ratio of the DC-DC converter is d_2

$$V_{dc} = d_2 V_{PV} \tag{13}$$

Figure 8 shows the voltage and current waveforms for pulse switching. Therefore the voltage rating of the IGBTs is given by

$$\text{Voltage rating} = V_{dc} = d_2 V_{PV} = V_{Grid} \tag{14}$$

Assuming that the efficiency of the DC-DC converter is η_{DC} and that of the converter is η_{pulse}

$$V_{Grid} I_{Grid} = \eta_{PV} \times \eta_{DC} \eta_{Pulse} \tag{15}$$

where I_{Grid} is the rms value of the ac current shown in Figure 4

Therefore the current rating of the switch is given by

$$\text{Current rating} = \frac{P_{PV} \times \eta_{DC} \eta_{Pulse}}{V_{Grid}} \tag{16}$$

Assuming that the ON state voltage drop of IGBT is V_{ON}, the conduction losses were calculated approximately as:

$$\text{Conduction losses} = 2 I_{Grid} \times V_{ON} \tag{17}$$

If the switching frequency is f_{pulse}, switching losses are approximately given by $V_{dc} I_{Grid} f_{pulse}$.

Table 1 summarises the components and their ratings required for the current scheme and the proposed scheme to interface the PV array to 33 kV network.

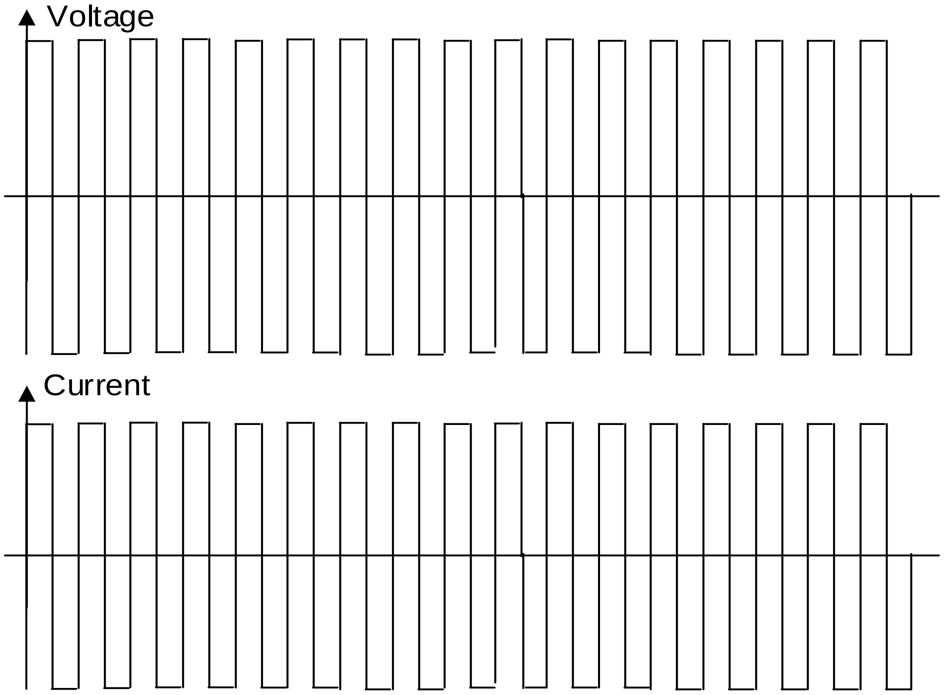


Figure 8: Current and voltage for pulse switching.

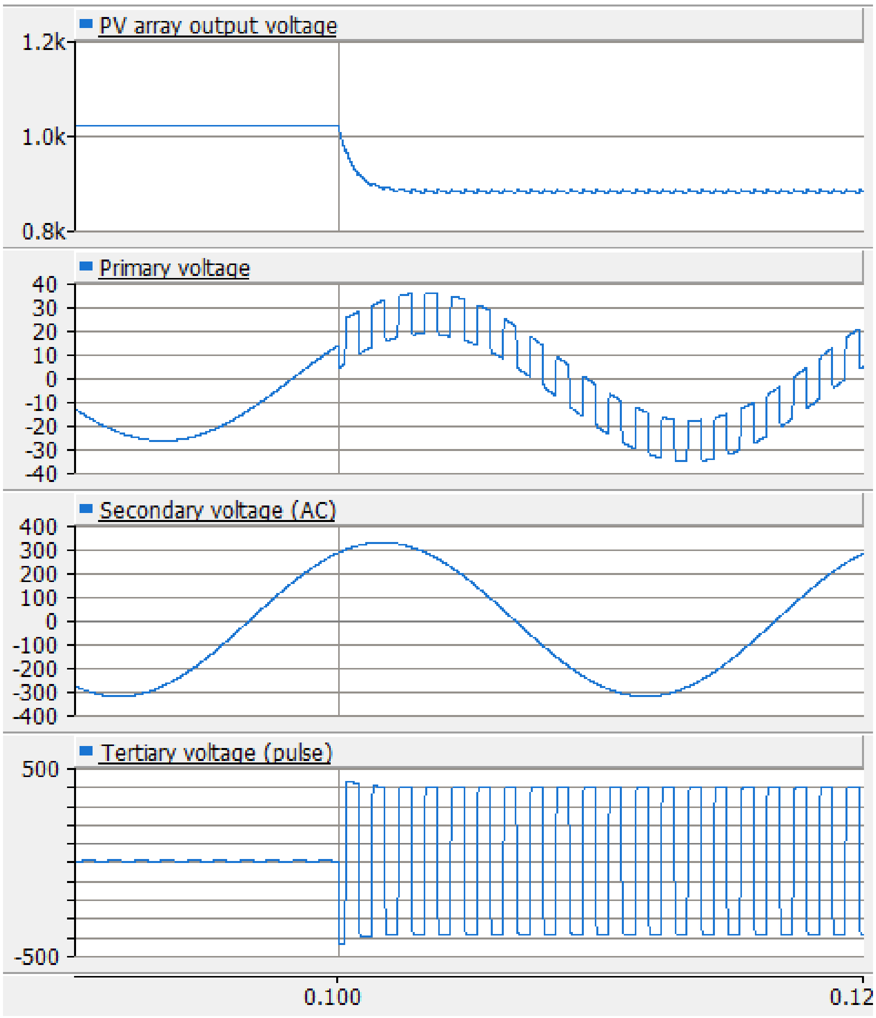
Table 1: Comparison of the AC and hybrid distribution of PV.

	AC distribution	**Hybrid distribution**	**Comparison**
Power electronic converters			
No of IGBTs	6	4	AC distribution scheme requires more IGBTs than the proposed scheme
Voltage rating of IGBTs	d_1V_{PV}	d_2V_{PV}	From equations (8) and (14), d_1/d_2 is 3.15
Current rating of IGBTs	$0.33\frac{P_{PV}\times\eta_{DC}\eta_{VSC}}{V_{Grid}}$	$\frac{P_{PV}\times\eta_{DC}\eta_{Pulse}}{V_{Grid}}$	Current rating of the IGBTs required for the proposed scheme is 3 time that of the AC scheme
Switching pattern	PWM switching	Square wave switching	In order to minimise the size of the filter required, PWM switching should perform in higher frequency than square wave switching
Conduction losses in IGBTs	$3\times I_{Grid}\times V_{ON}$	$2\,I_{Grid}\times V_{ON}$	Conduction losses are higher in the AC scheme
Switching losses in IGBTs	$3V_{dc}I_{Grid}f_{PWM}$	$V_{dc}I_{Grid}f_{pulse}$	Since $f_{PWM}>>f_{pulse}$ swiching losses are much higher in the AC scheme
132/33 kV Transformer			
VA rating	Equal to the total load Both carries VA rating of all AC loads plus all DC loads		
Cu losses	Equal as both transformers are identical		
Iron losses	Only 50 Hz current flows thus iron losses are less	High frequency current flows in the secondary thus losses are high	Iron losses include hysteresis losses proportional to fB^x and eddy current losses proportional to f^2B^2
33/1 kV Transformer			
Winding arrangement & foot print	Three phase 50 Hz transformer	A single phase high frequency transformer	The foot-print of the single phase high frequency transformer is much smaller than the 3-phase transformer.
Cu losses	$3I_{pv,p}^2R_p$	$I_{pv,1p}^2R_{1p}$	Per phase current in AC scheme will be lower than single-phase transformer. Thus Cu losses in the hybrid distribution may be higher than AC scheme.
Iron losses	Only 50 Hz current flows thus iron losses are less.	High frequency current flows thus losses are high	AC scheme utilises a 3-limb or 5-limb core thus core area is much higher than that required for the high frequency transformer. This increases the losses.

33/0.4 kV Transformer			
Winding arrangement & foot print	Three phase two winding transformer	Three phase three winding transformer	Even though the proposed scheme has a secondary and tertiary windings the addition of their VA rating is equal to the VA rating of the secondary of the AC scheme. Therefore the foot print may be comparable.
Conduction losses	Three phase transformer Cu loss plus all the losses in the downstream AC to DC converters	Three phase transformer Cu loss plus losses in the rectifier that used to convert pulse output to DC	As the VA ratings of both schemes are equal and the losses associated with AC to DC converter is high, the conduction losses of the AC scheme may be much higher
Iron losses	Only 50 Hz current flows thus iron losses are less.	High frequency current flows thus losses are high	

Table 2: System parameters.

Component	Parameter	Value
PV array	No of modules in series	27
	No of modules in parallel	58
	No of cells in series per module	60
	No of cell sting in parallel per module	2
	Power output of each module	250 W
	Open circuit voltage of the module	37.8 V
	Short circuit current of the module	8.89 A
	Cell area	78 mm x 156 mm
	Series resistance	0.02 Ω
	Shunt resistance	1000 Ω
	Diode ideality factor	1.0694
High frequency transfer	Ratio	1 : 10 kV



All voltages are in V

Figure 9: Voltage at different points.

SIMULATION STUDY

System under study

In order to perform the simulation study the system parameters given in Table 2 were used.

Ratios of the three winding transformer was selected such that per phase secondary AC voltage is equal to 230 V and DC voltage is equal to 380 V.

From equation (4), the rms value of the AC voltage $V = \sqrt{3}k' \times \frac{33\times 10^3}{\sqrt{3}} = 230$ and

$k' = 0.007$.

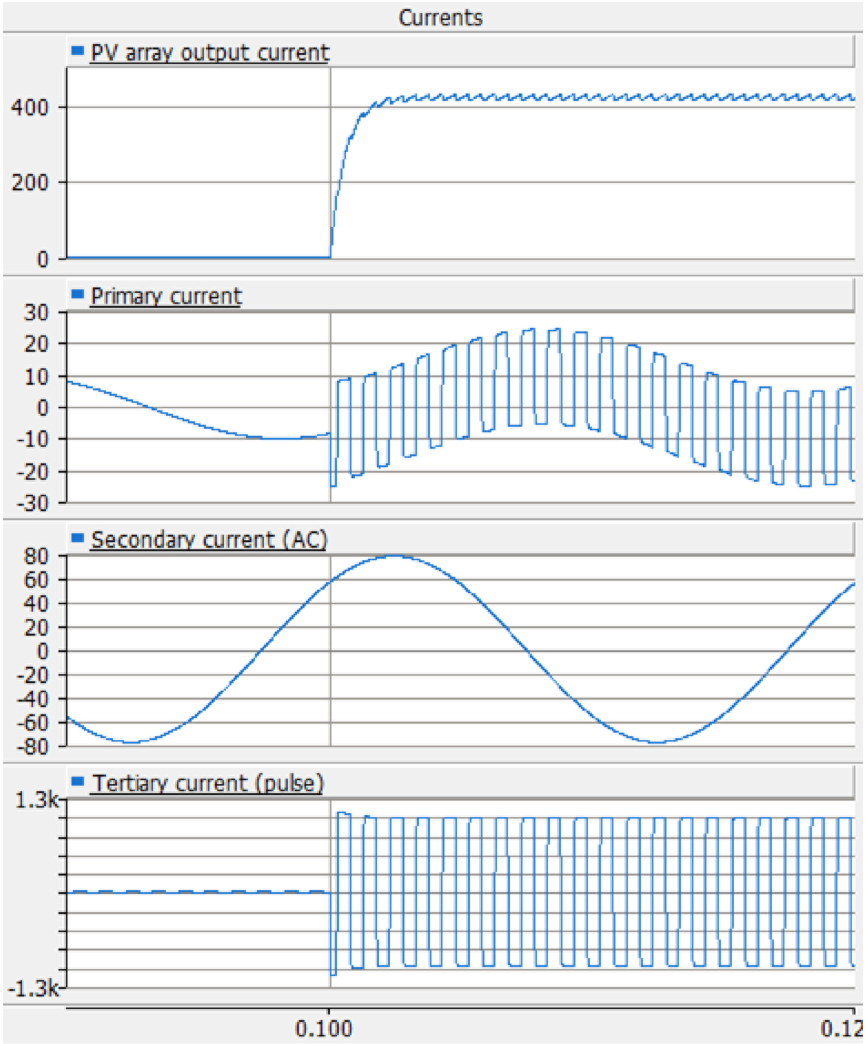
From equation (5), the DC voltage $= 3k''\left|v_{pulse}(t)\right| = 380\,\text{V}$

Since $\left|v_{pulse}(t)\right|$ = 27 x 31.2 (output voltage of the PV array) x 10 (pulse transformer ratio) = 8.5 kV.

Therefore, $k'' = 0.015$

Simulation results

The circuit shown in Figure 2 was implemented in PSCAD/EMTDC simulation environment. It was assumed that the AC load is unity power factor. Figures 9 and 10 show the PV array output and three winding transformer currents and voltages. The PV panel was open until 0.1 sec and then connected to the circuit.



All currents are in A

Figure 10: Currents at different points.

PRACTICAL IMPLEMENTATION

In laboratory implementation shown in Figure 11, two similar types of transformers were used as the injection transformer and the separation transformer. Transformer tapping voltages were used accordingly. They are rated at 2 kVA with a primary voltage of 220 V and Secondary/Tertiary voltage of 63.5 V.

After the injection of pulse voltage into the neutral point of the injection transformer secondary, the hybrid waveform was obtained. Pulse signal is superimposed on AC signal as shown in Figure 12.

Figure 13 shows the output of the separation transformer. As can be seen both AC and pulsed DC can be extracted from the separation transformers.

Secondary and tertiary voltages expected for given input voltages were calculated using equations (4) and (5). They are compared in Table 4. Even though the output voltage of both injection and separation transformers are comparable, the output pulse voltage shows a considerable difference. This is mainly due to the distorted pulse voltage obtained experimentally (Figure 13(b)).

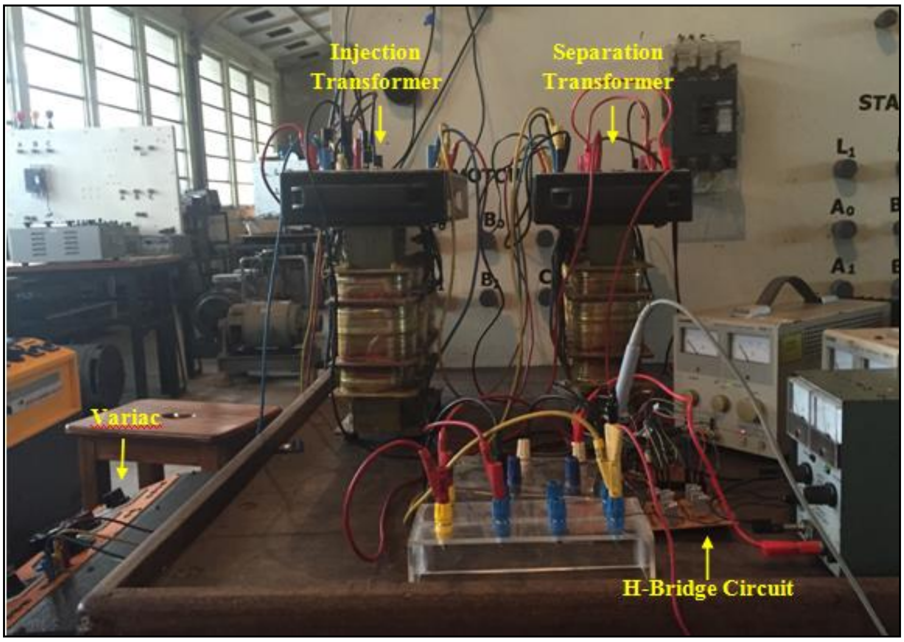


Figure 11: Laboratory setup.

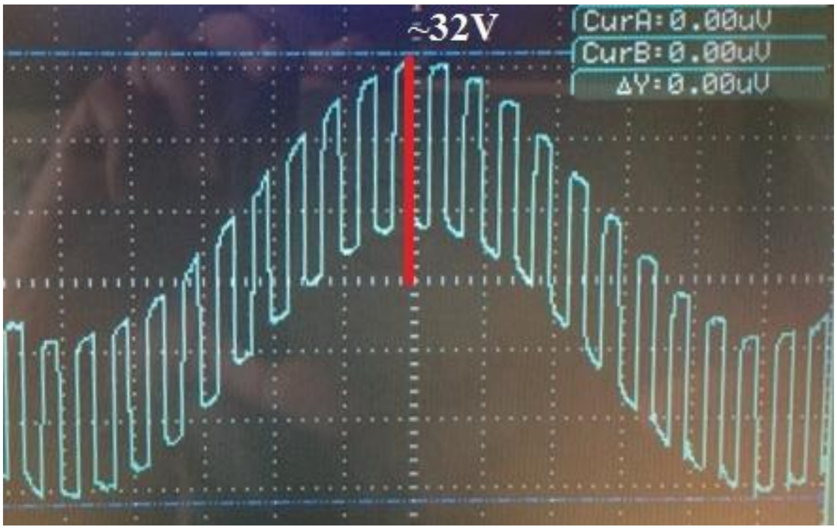
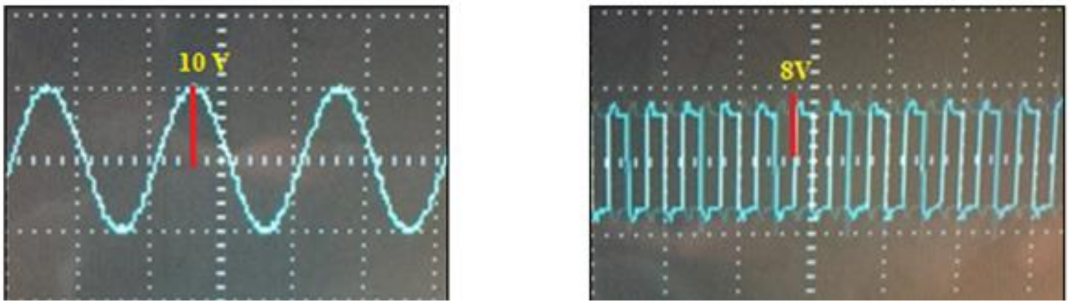


Figure 12: Output of the injection transformer when 12V pulse is injected from the neutral.



(a) **(b)**

Figure 13: Outputs of separation transformer. (a) AC voltage from the secondary. (b) Pulse voltage from the tertiary.

Table 4: Calculated and experimentally obtained output voltages.

Parameter		Calculated voltage (V)	Experimentally obtained voltage (V)
Injection Transformer	Maximum of output voltage	32.2	32
Separation Transformer	Output AC voltage (rms)	7.15	7.07
	Output pulse voltage (max)	10.39	8

CONCLUSION

With increasing demand of electricity, means of improving energy efficiency is a must. It is well recognised that energy losses in conversion stages when connecting renewables to AC system at the source end and when connecting many consumable loads at the demand side incur losses. These losses can be eliminated if loads are fed with AC or DC depending on the nature of the load. Further, in order to improve the efficiency of the overall system, it is important to integrate renewable energy sources such as PV and wind with minimum energy losses.

This paper presented a hybrid distribution system that can enhance the energy efficiency of medium and low voltage distribution networks. An injection transformer and a separation transformer was designed to inject renewable energy sources in an energy efficient way and to supply AC and DC loads directly. The concept was proved using simulations and practical implementation. Further, a comparison was made to show the rating of different components and losses associated with different systems in AC and the proposed schemes.

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