Interfacing DC renewable energy sources with the AC Distribution System

S. A. Hafidz and K. P. Basu

Abstract—**Interfacing technique of dc renewable energy sources like photovoltaic (pv) solar generators with ac distribution line employs inverter, producing higher cost and Power Quality (PQ) problems. A standalone pv generator also needs battery support for energy storage. In an earlier paper [1] it was proposed to utilize two zigzag transformers to interface any dc power source with an ac distribution line fed from a delta connected 3-phase supply. Ac and dc power simultaneously flows through the 3-phase line. The return path of dc is through the ground. Existing substation batteries are used as energy storage device and no inverters are required. It has been established earlier that zigzag transformer with the neutral grounded regenerates open phase voltage during 1-pole auto reclosing in distribution feeders [2]. This distribution feeder may supply 3-phase unbalanced and 1-phase load. The presence of dc voltage in the three phase wires along with the ac voltage may create disturbance in the flow of load current. The load may carry not only alternating current but also unwanted direct current. To avoid the dc current flow through the load, it is proposed to connect a separate wire from negative of the substation battery to the negative of the dc renewable energy source.**

Keywords—**solar pv generator, fuel cell, ac-dc power flow, zigzag transformer, storage battery, inverter, grid interfacing**

I. Introduction

Solar and wind energy are non-polluting renewable 'green energy'. Conventional energy sources like thermal, hydro and nuclear generators produce ac but photovoltaic (pv) solar generators produce dc power. The absence of sunlight during night and the change of its intensity in the days throughout a year make the solar pv generator unreliable. Effective use of pv solar generation and proper harnessing of its power, energy storage devices like storage batteries, are extensively used in standalone solar pv generation [3-5] system. The price and maintenance cost of batteries increase the cost of solar energy, thereby causing its use uneconomical.

Other dc power sources, namely, fuel and biogas cells, are commonly used in disperse power generation [6].

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The variable frequency synchronous generator coupled with the wind turbine produces ac variable frequency and by rectification dc power is obtained.

Interfacing dc power generated by solar pv generators and other sources with the national grid increase the reliability of the operation of these dc sources. The commonly adopted interfacing technique [7-9] is to connect a power semiconductor converter to feed the dc power generated from these sources to the ac power of the national grid by inversion and to draw the dc power from the grid by rectification. The converter is not only expensive but it causes PQ disturbance in the grid supply system.

In an earlier paper [10] the authors has established the possibility of transmission of ac and dc power simultaneously through the same transmission line. Using the same principle a new technique [1] was proposed. In that paper dc power source was interfaced with the high voltage distribution system of the national grid with the help of two zigzag connected transformers. The existing resources in the distribution system like storage batteries, battery chargers, dc loads and the grounding transformer in the substation are used either to consume or to deliver dc power through the distribution line. The cost of interfacing is highly reduced and the PQ problem is eliminated.

II. High Voltage (HV) Distribution System

Distribution lines (generally 6.6 – 33 kV) in association with the distribution substations are the basic components of a hv distribution system. A pv or any other type of dc power generator may be situated very near to a hv distribution line. Transmission lines (132 – 765 kV) supply power to the distribution substation though one or more star-delta transformers. The delta side of the transformer feeds power to the hv distribution lines and there is no ground connection. Zigzag winding grounding transformers connected to the distribution substation busbars provide the path for ground fault current. Storage batteries are installed in the substation to provide emergency as well as normal dc power supplies to the substation loads. The substation battery chargers supply quick or floating charge to the batteries.

III. Proposed Technique of Interfacing

The proposed technique for interfacing a dc power source with a hv distribution line is illustrated in Fig.1. The neutral point of the first zigzag transformer (ZT_1) is directly connected to the positive terminal of dc source. The negative terminal of dc source then is connected to the ground. Local

ac load will be supplied through ZT_1 from its low voltage secondary winding. The neutral point of the second zigzag transformer (ZT_2) is connected to substation batteries and dc loads. ZT_2 is also used to work as the grounding transformer of the distribution substation fed from the delta-connected secondary of the power transformer and is already present in the system.
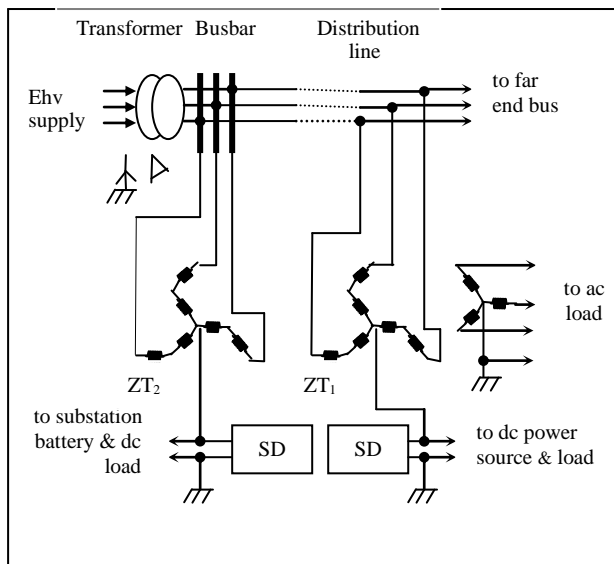

Figure 1.   Proposed interfacing technique

The zero sequence voltage is absent from the distribution line under the normal operating condition. Positive and/or negative sequence voltages produce no potential difference between its neutral point and ground at the hv terminals of the transformer. At the neutral point of the zigzag transformer, the phasor sum of positive/negative sequence currents is also zero and therefore the hv ac supply does not impose any restriction on the connection of dc power supply or the battery between the neutral point of the zigzag transformer and ground.

The dc current (I_{dc}) from the dc power source flows through the windings of ZT_1, three-phase conductors of the distribution line, windings of ZT_2, substation storage batteries/dc loads, and the ground. The dc current is equally divided in all the three phases as the resistances being equal in all the three phases of ZT_1, ZT_2 and the three conductors of the line. The dc current produced two fluxes ($I_{dc}/3$) equal in magnitude and opposite in direction flowing through each half of a winding in each limb of the core of a zigzag transformer. So the net dc flux at any instant of time becomes zero in each limb of the core of ZT_1 and ZT_2. Thus the dc saturation of the core is avoided. Zigzag transformers provide very high (magnetizing) impedance to positive and negative sequence currents. However, they provide a very low resistance path to the dc current. The ac (I_{ac}) and the dc ($I_{dc}/3$) currents simultaneously flow through each phase conductor of the distribution line. The return path of the dc current is through the ground.

The local dc load (R_{dc1}) consumes a part of power source when the dc power source is generating rated power. The excess generation may be used to charge the substation batteries and to deliver power to the remote dc load (R_{dc2}) of

the substation through ZT_1, distribution line and ZT_2. The dc load R_{dc1} may be supplied from the substation battery charger through ZT_2, distribution line and ZT_1 when the dc power generation is inadequate. ZT_1 may supply the local ac load of the dc power generating plant through its low voltage secondary winding, which serves as interfacing-cum-service transformer. Inversion of the dc supply for interfacing with the hv ac distribution line and to supply the local ac load is not required and is completely avoided. Rectification of the ac power supply from the distribution line is not required as well.

For protection against high voltage surges during phase to ground fault in the distribution line, surge diverters (SD) are connected across the dc generating source and substation batteries. Both ZT_1 and ZT_2 neutrals are connected solidly or through grounding resistance to the earth to provide ground fault protection and to secure the safety of the dc power source and the battery at the initiation of a line to ground (LG) fault. The change over from the normal connection to the earth connection (not shown in Fig.1) is activated by the ground fault relay of the distribution line.

IV.   **Mathematical Formulation**

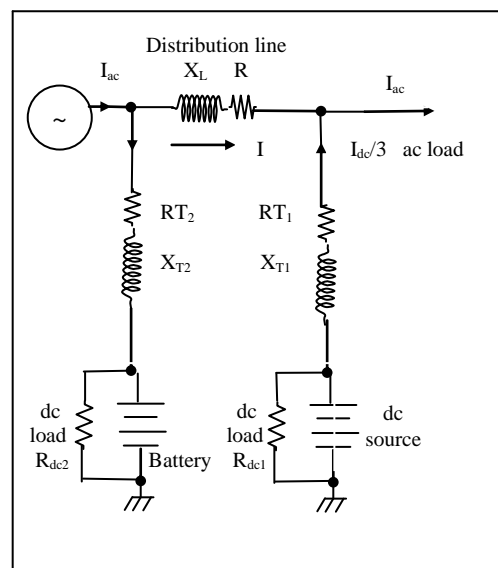The equivalent circuit of the combined ac-dc system is shown in Fig.2.

Figure 2.   Equivalent circuit

RT_1, RT_2 are the dc resistances and XT_1, XT_2 are the magnetizing reactance of the zigzag transformers ZT_1 and ZT_2 respectively. X_L and R are the reactance and resistance per phase of the distribution line. Each conductor of the line carries one-third of the dc current along with the ac current. The equivalent resistances offered by ZT_1, ZT_2 and the line to I_{dc} are $RT_1/3$, $RT_2/3$ and $R/3$ respectively. The ac current flow is restricted between the zigzag connected windings and the three conductors of the distribution line in the absence of zero sequence and third harmonic voltages under normal operating condition. I_{ac} being the rms ac current per conductor at any point of the line, the total rms current per conductor becomes:

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$$I = [I_{ac}^2 + (I_{dc}/3)^2]^{1/2} \qquad (1)$$

The total power loss in the line is:

$$P_L = 3I^2R \qquad (2)$$

The voltage drop in the line due to the dc current is $RI_{dc}/3$ and is negligible in comparison to the voltage drop due to I_{ac}. The total current I in any phase conductor is asymmetrical but two natural zero crossings in each cycle in the current wave are obtained for $(I_{dc}/3I_{ac}) < \sqrt{2}$. For any short circuit in the hv line the above relationship is always satisfied and the conventional circuit breakers used to interrupt ac current may be employed for protection. Costly dc circuit breakers are not required. The instantaneous value of each conductor voltage with respect to ground is the dc voltage V_{dc} with a superimposed sinusoidal ac voltage having rms value of E_{ph} and the peak value being:

$$E_{max} = V_{dc} + \sqrt{2}E_{ph} \qquad (3)$$

Each conductor is to be insulated for E_{max} but the line to line voltage has no dc component and:

$$E_{LL(max)} = \sqrt{6}E_{ph} \qquad (4)$$

Therefore, the rated ac voltage of the line determines conductor-to-conductor separation distance. The magnitude of the dc power flow in either direction between the distribution substation and the remote dc power source is low, as it is confined to charging the battery and supplying power to either R_{dc1} or R_{dc2}.

TABLE 1. AC-DC POWER FLOW DATA

Rated line voltage V_{LL} (kV)	33	11	6.6	0.43
Rated line power MVA (ac)	5	1	0.5	0.1
Maximum dc power transfer (kW)	10	10	10	10
Dc voltage V_{dc} (Volt)	250	250	250	250
Maximum dc current I_{dc} (Amp)	40	40	40	40
Rated rms line current I_{ac} (Amp)	87.5	52.5	43.7	134.3
Maximum rms current I (Amp)	88.5	54.2	45.7	134.9
Peak phase to ground voltage E_{max} (kV)	27.19	9.23	5.63	0.60
Peak phase voltage $E_{ph(peak)}$ (kV)	26.94	8.98	5.38	0.35

Table 1 gives values of currents and voltages for four different distribution lines interfaced with a dc source. A representative value of 10 kW power flow (on the higher side) at 250 V dc is assumed [9].

From the tabulated data it is observed that the difference between maximum rms current (I) and the rated line current (I_{ac}) is very small. So the distribution line can safely carry the additional dc current without being overloaded. Similarly the peak phase to ground voltage E_{max} slightly exceeds the peak phase voltage $E_{ph(peak)}$. Therefore, there is no need to increase the insulation level of the line conductors and the existing insulators may be used.

The dc power loss should be kept low to improve the efficiency of the power flow. The total resistance offered to the dc current is:

$$R_{dc} = (RT_1 + R + RT_2)/3 + R_r \qquad (5)$$

The resistance (R_r) of the dc current return path may be reduced to a minimum by using a ground wire, seawater or the metallic sheath of a cable as the return conductor. Reduction of the magnitude of dc power flow through the line also improves the efficiency. In this context it is to be noted that the efficiency of an inverter used in the conventional interfacing method is of the order of 90% [9].

V. Cost Benefit

The storage battery, battery charger and the grounding transformer ZT_2 are already present in the existing hv ac distribution substation. The cost of the other interfacing-cum-service transformer ZT_1 is comparable to that of the hv transformer required for connecting an inverter to the distribution line for interfacing dc renewable energy source in the conventional method. Thus the additional investment and maintenance cost on inverter and/or storage battery are avoided.

VI. AC Load in the Distribution Line

There is no problem in charging the battery from the renewable energy dc source. But the dc voltage present in the phase wires of the distribution line will try to push unwanted dc current through the ac loads of the distribution system. The net current in the ac load will be the combination ac and dc current.

To avoid the dc current flow through the ac load it is proposed to connect negatives of the batteries (refer Fig.3) by a separate wire and the ac load is connected to ground. The ground connection of pv solar cell is removed and ZT_1 neutral is grounded. Under normal operation if zigzag transformer neutral connected to a dc source (pv source), the voltage in all phases can be maintained. The dc voltage which is generated from renewable energy can be used to supply the dc load. Ac load will get the supply from other distributed generators (DGs) in distribution network.
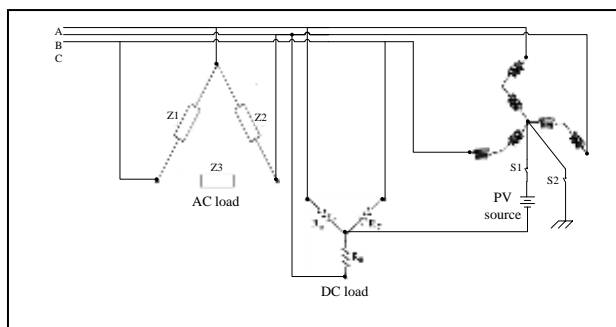
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Figure 3. Ac and dc loads in distribution network

VII. Conclusion

A dc power source may be interfaced with a high voltage distribution line fed from a delta connected ac supply by using two zigzag transformers one at the source end and the other at the distribution substation. Ac-dc power simultaneously flows through the line. The latent resources of the distribution system are efficiently used to reduce the cost of interfacing. The existing storage batteries, battery chargers and a grounding transformer at the distribution substation are utilized in the interfacing technique. Inverters used in the conventional ac-dc interfacing method are not required. Separate Batteries employed with the stand-alone pv solar generators for energy storage are not needed. The efficiency of the dc energy transfer improves with the lower value of the resistance offered to dc current flow. The proposed interfacing technique does not create any power quality problem due to the absence of inverter.

The problem appears when ac load is supplied through the distribution line. It can be avoided by connecting the negatives of the pv solar cell battery and the station battery by a separate wire.

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