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Voltage regulation in electrical supply substations for DC traction systems

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Abstract

All metrorail plants and a large number of railway plants in the world are fed by electrical supply substations equipped with AC/DC conversion units. The most common rectifier configuration for the application is the parallel 12-pulse, which features low harmonic distorsion of AC line current and DC voltage, together with acceptable structure complexity and cost. The rectifiers are normally equipped with diodes and voltage regulation is not performed. In this paper the authors review some converters configuration suitable for voltage regulation and compare them on the basis of their impact on the operation of the plant.

Introduction

In a metrorail or railway system DC voltage drop at each substation terminals (and consequent voltage drop alomg the traction line) can result in bad load sharing between substations and reduction of plant capacity and exploitation. Voltage regulation is then often auspicious, particularly for upgrading of existing plants performance in case of increased traffic demand, for line voltage profile optimization, for appropriate load sharing and maximum exploitation of the plants, in terms of headway decrease (or increase of the number of circulating trains).

In electrical supply substation equipped with diode rectifiers, the relationship between the average DC voltage and the average DC current is imposed by the output characteristic of the conversion unit, as it is shown in Figure 1 [3], for the 12-pulse unit used by the Italian State Railways (3600 V rated DC voltage, 1500 A rated DC current, 5400 kW rated DC power) [4]. The slope of the V-I curve can be partially controlled by means of appropriate

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design of the unit transformer (leakage reactances and reactance ratio) [5] and in the normal load operation range such slope is equal to $-3X_c/2\pi$, where X_c is the commutation reactance of the transformer, proportional to the short circuit voltage (plus primary line reactance if significant). The equivalent resistance $R_{eq} = 3X_c/2\pi$ is normally defined, as the conversion units behaves like an ideal voltage source with the series equivalent resistance R_{eq}. Overloading, which is allowed and frequent during rush hours, can produce even higher voltage drops, as the slope of the above curve increases as average DC current increases.

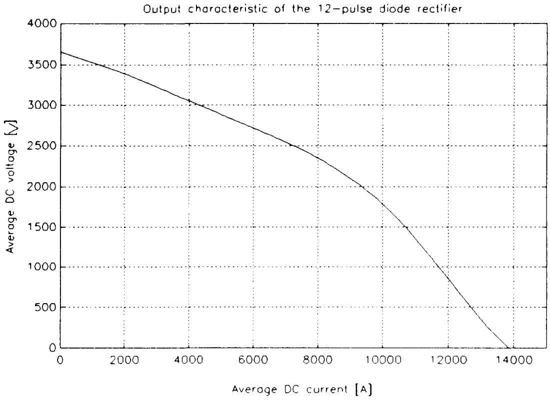

Figure 1

The simplest way to perform voltage regulation on the DC side of the conversion units is to utilize the automatic tap changer at the primary windings of the unit transformer. This method has been sometimes utilized, but it can perform discrete regulation only, with extremely slow dynamics. These two limitations make the method useless with respect to significant benefits to the operation of the plant.

Booster conversion units

If diodes are replaced by thyristors, electronic voltage control can be performed, with good precision and dynamics. The complete replacement of the present diode rectifiers with fully controlled ones probably is not the best solution for existing plants, particularly in terms of cost. Some alternative stuctures can be taken into account, particularly the *booster* schemes. The basic booster conversion unit is shown in Figure 2, where the main diode rectifier and the booster rectifier are reported. The booster rectifier is a fully controlled (thyristor) rectifier which is expected to carry the whole output current of the substation, but manages only a fraction of the total output voltage (say $25\%V_{d0}$, where V_{d0} is the no-load output voltage of the diode rectifier R). Rectifier B is then rated for a corresponding fraction of the substation rated

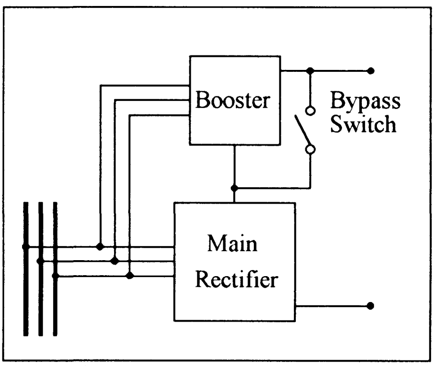

Figure 2: Booster conversion unit.

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power. Moreover, in case of failure of the booster rectifier, less reliable than the main one, the substation can still operate in the non-controlled mode thanks to the by-pass switch shown in Figure 2.

Several booster structures can be considered as a function of the design objective: a new plant or a upgrade of an existing plant. The different structures can be compared with the reference totally controlled 12-pulse scheme. In each case the control system is designed in order to keep the DC voltage constant independently from the load current. This is one of the possible voltage regulation methodologies, and implies to compensate the inductive voltage drop by appropriate control of the firing delay angles of the booster thyristors. Other methods can be oriented to different objectives, such as energy saving, losses minimization and optimized load sharing. These methods involve the operation of a central supervising apparatus, whose features are indirectly taken into account in the paper.

Converter configurations

The following converter configurations have been considered:

1. 6-pulse main rectifier with 6-pulse booster rectifier (the booster is fed by to transformers connected to the secondary windings of the main rectifier transformer, in order to balance the load between the two windings;
2. 6-pulse main rectifier with 6-pulse booster rectifier (the booster is fed by a single transformer connected to one of the secondary windings of the main rectifier transformer);
3. 6-pulse main rectifier with 6-pulse booster rectifier (the booster is fed by a single transformer connected to primary side of the main rectifier transformer, in order to avoid load unbalance between the two secondary windings);
4. 12-pulse main rectifier with 6-pulse booster rectifier (the booster is fed by a single transformer connected to one of the secondary windings of the main rectifier transformer);
5. 12-pulse main rectifier with 6-pulse booster rectifier (the booster is fed by a single transformer connected to primary side of the main rectifier transformer, in order to avoid load unbalance between the two secondary windings);
6. 12-pulse main rectifier with 12-pulse booster rectifier (the booster is fed by two equal transformers connected to the secondary windings of the main rectifier transformer, in order to avoid load unbalance between the two secondary windings);
7. 12-pulse main rectifier with 12-pulse booster rectifier (the booster is fed by a double secondary transformer connected to the primary side of the main rectifier transformer);
8. reference fully controlled 12-pulse rectifier.

The above converter configurations are shown in Table 1.

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Simulation

All the above options have been implemented for digital simulation with the general purpose circuit simulator ATP [1][6]. The characteristics of the eight types of concerters have been compared on the basis of three parameters:

- power factor ($\cos\varphi$);
- Total Harmonic Distorsion of AC current (THD%);
- Distorsion of DC voltage (V_r).

Within ATP the power factor has been evaluated according to the relationship:

$$\cos\varphi = \cos\left(a\tan\left(\frac{Q}{P}\right)\right)$$

where the reactive power Q and the real power P are easily evaluated in the distorted steady state according to the instantaneous real and reactive power theory [7].

The total harmonic distorsion of the AC current is evaluated on the basis of the conventional formula:

$$THD\% = \frac{\sqrt{\sum_{h=2} I_h^2}}{I_1} 100$$

where I_h is the amplitude of the h-th current harmonic and I_1 the amplitude of the fundamental [2].

The DC voltage distorsion is given by:

$$V_r = \sqrt{\sum_{h=1} V_h^2}$$

where V_h is the RMS value of the h-th DC voltage harmonic. V_r represents the global RMS value of the voltage ripple.

Each of the above parameters has been evaluated for three different values of the average DC current. Particularly, the cases with I_{DC} = 1, 2, 3 kA have been considered, in order to verify the effect of the inductive voltage drop. The firing delay angle of the thyristors have been choosen in order to have constant DC voltage at the substation terminals, so that the firing delay angle is maximum in no-load conditions and almost zero in maximum load conditions. Actually, the rated secondary voltage of the booster transformer has been choosen in order to compensate the maximum inductive voltage drop with zero firing delay angle.

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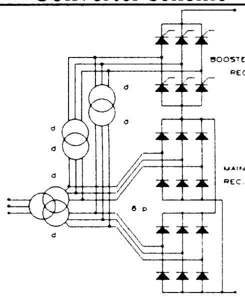
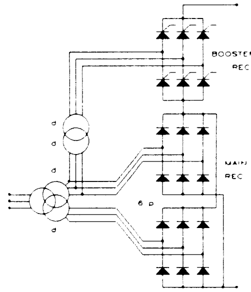
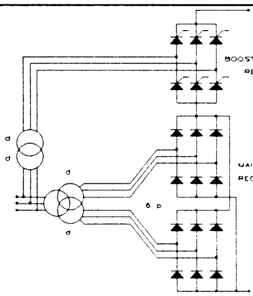
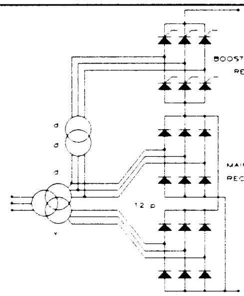
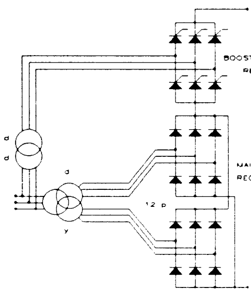
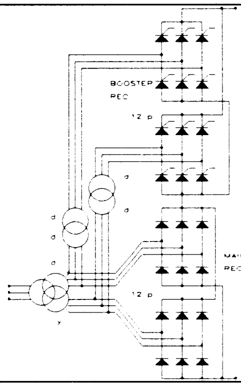
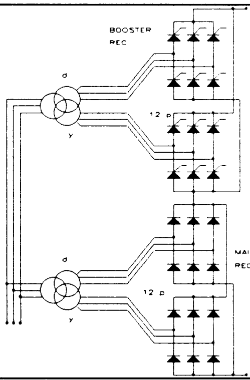
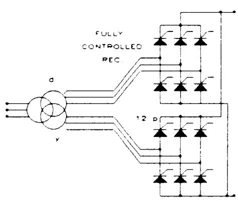
N.	Converter scheme	N.	Converter scheme
1		2	
3		4	
5		6	
7		8	

Table 1.

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Comparison and conclusions

The bar charts in Table 2 and the results summary in Table 3 show that the eight converter configurations can be grouped according to the following criteria:

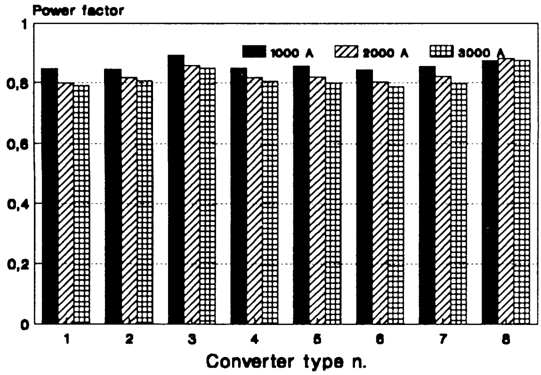
- 6-pulse main rectifier and 6-pulse booster rectifier
- 12-pulse main rectifier and 6-pulse booster rectifier
- 12-pulse main rectifier and 12 pulse booster rectifier

The best global behaviour, in terms of AC current Total Harmonic Distorsion, power factor and DC voltage ripple is presented by the fully controlled 12-pulse bridge. All the conversion units with 12-pulse main rectifier (converters type n.4, 5, 6, 7, 8) present better features, with particular regard to the distorsion of the AC current. From the power factor bar chart it can be observed how the 12-pulse fully controlled rectifier presents the best power factor in any load condition. The power factor is always larger than 0.87. The low load operating conditions must be excluded, as the power factor is low, but the power supplied by the line is low too. The 12-pulse fully controlled rectifier appears to be the most significant option for the application, certainly from the point of view of the quality of the power supplied to the traction load and absorbed by tha three phase network. Moreover, the 12-pulse fully controlled rectifier presents the simplest power circuit configuration: one single double secondary transformer, one single 12-pulse bridge. The disadvantages of the utilization of the 12-pulse fully controlled bridge are the low flexibility and the need of complete replacement of the old units in case of upgrading of existing plants. Converters type n. 1, 2, 3 are not adequate for the application: the general trend is however already to utilize 12-pulse rectifiers, both for metrorail and railway systems.

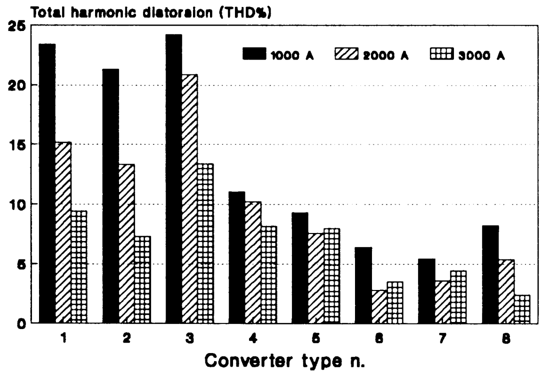
In case of new plants it is appropriate to utilize 12-pulse fully controlled rectifiers: it is interesting to note how the fully controlled bridge can be utilized also for short circuit current protection by suppression of the thyristors firing pulses.

In case of existing plants where the electrical supply substations are equipped with 12-pulse diode rectifiers, the most interesting solution is to add a 12-pulse booster rectifier with one double secondary transformer fed directly by the main line. This solution maximizes both the power quality and the cost of the converter, but is probably the only one acceptable in terms of AC current harmonic distorsion. Converter n. 5 can be otherwise considered, as it presents acceptable characteristics.

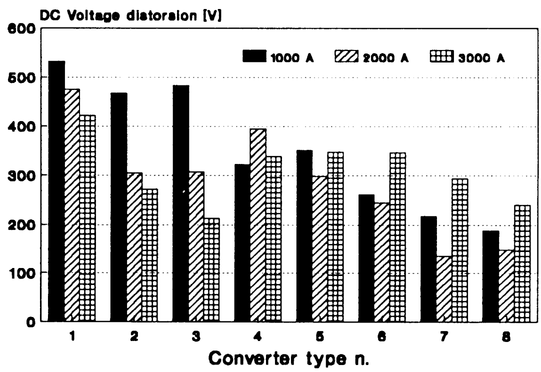
On the basis of the present technical considerations and after the appropriate evaluation of reliability and cost issues, in each specific application the converter for DC voltage regulation can be choosen.



Converters power factor for 1, 2, 3 kA DC current



Converters AC line current THD% for 1, 2, 3 kA DC current



Converters DC voltage distorsion for 1, 2, 3 kA DC current

Table 2.

	I_{DC} = 1000 A			I_{DC} = 2000 A			I_{DC} = 3000 A		
	cosφ	THD%	V_r [V]	cosφ	THD%	V_r [V]	cosφ	THD%	V_r [V]
1	0.846	23	532	0.799	15	475	0.790	9	412
2	0.845	21	468	0.817	13	305	0.807	7	272
3	0.892	24	483	0.858	21	307	0.848	13	213
4	0.847	11	322	0.817	10	394	0.805	8	338
5	0.856	9	350	0.819	7	298	0.799	8	347
6	0.843	6	261	0.803	3	245	0.786	3	346
7	0.854	5	217	0.820	4	136	0.786	4	293
8	0.874	8	188	0.880	5	148	0.873	2	240

Table 3.

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