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SIZING NOTE

HOW TO DETERMINE COMPONENT RATINGS WHEN APPLYING AN AUTOMATIC VOLTAGE REGULATOR

1. INTRODUCTION

COMPONENT RATINGS FOR PROPER VOLTAGE REGULATION

When retrofitting or installing a system containing an automatic voltage regulator to correct system voltage sags and swells, it is critical to coordinate breaker, step-down-transformer and voltage regulator ratings. This process, while straightforward, is often complicated by commercial considerations, such as the ratings of existing equipment or the magnitude of sags and swells.

In this discussion, we examine voltage and current requirements of system components – from input breaker to step-down transformer to voltage regulator – when supplying a typical system. A load provided with constant power (kW or kVA) in a situation with variable source voltage must accommodate the current drawn from the source to vary inversely to the change in voltage to supply the required power (S=V x I).

2. THE BASICS: AUTOMATIC VOLTAGE REGULATOR SYSTEMS

In a perfect world, utilities would deliver power without voltage swells or sags. But the reality is that supply voltage is often higher than normal (a swell) or lower than nominal (a sag) over extended periods of time. To address these unacceptable power deviations, it is common to install an automatic voltage regulator (AVR) either before or after the step-down transformer. In doing so, it is important to determine the effect that installing the voltage regulator will have on existing system components.

2.1 SAMPLE BASE SYSTEM

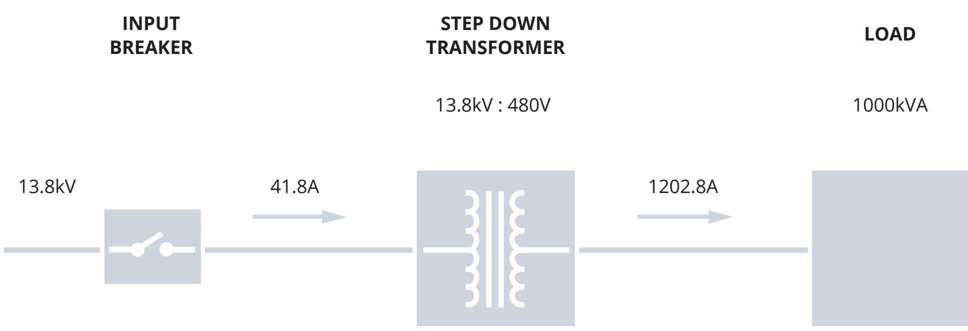

FIGURE 1: Example System – 13.8 to 480V. 1000kVA Load. Diagram represents a 3-phase system. Voltage is line to line. Currents are per phase.

The example base system depicted as Figure 1 has a sample input of a 60Hz 13.8kV phase-to-phase supply with a maximum load of 1000kVA at 480 volts. In optimal conditions (no voltage swells or sags), the power supplied to this base system at 13.8 kV would be reduced to 480 volts with a 13.8kV to 480 step-down transformer. As noted in Figure 1, the current on the 13.8kV line would be 41.8 amperes when the load is at its maximum level of 1000kVA, and the transformer would be rated and designed to carry this current level. The current on the low-voltage side would then be 1202.8 amperes per line (the same current necessary to supply power to the load at 480 volts). Normally, the input breaker trip level would be set at 133% of full-load current – or 55.6 amperes.

For purposes of this discussion, the regulator is located on the low-voltage side of the transformer. (If the regulator were to be placed in front of the step-down transformer, the analysis would be similar and the conclusions identical.) This discussion also assumes that the regulator in Figure 1 mitigates voltage swells of up to 10% and sags down to 75% (-25%) of nominal voltage. This level of capability addresses the vast majority of system power-quality events and is representative of commercially available voltage regulators applied on the low-voltage side of a step-down transformer.

2.2 SYSTEM WITH AVR AT LOW-VOLTAGE END OF TRANSFORMER

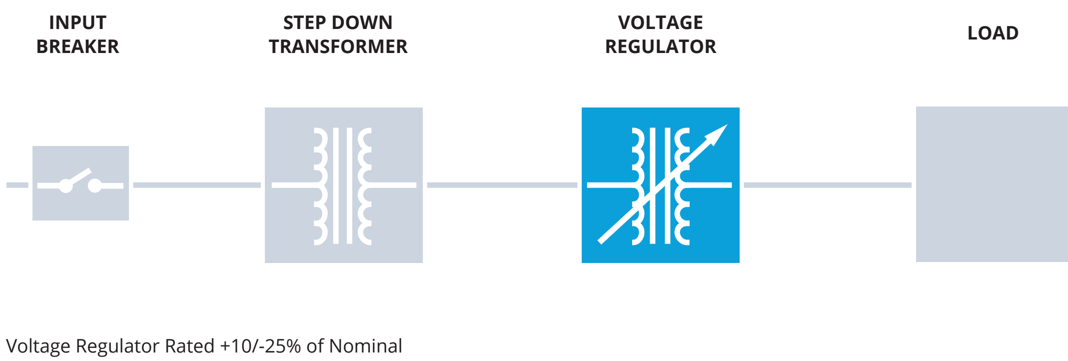

FIGURE 2: System with variable input voltage corrected by using a voltage regulator.

Figure 2 depicts a base system with an automatic voltage regulator on the low-voltage side of the step-down transformer. For analysis, at an instant of time, the voltage regulator simply acts as a transformer with a fixed turns ratio. The turns ratio is determined by the system's need to buck or boost the output voltage of the step-down transformer, based upon voltage delivered by the source to the step-down transformer input.

For example, if the system delivers voltage that is 15% below the nominal or desired system voltage, the regulator is responsible for boosting the voltage by 17.65% (1.0/0.85). As such, the regulator acts as a transformer with a turns ratio of 1 to 1.1765. Now, this instant-of-time analysis can be performed simply by noting the transformation ratio of the two transformers – specifically the required range of current and voltage for each system component as a function of the input system voltage and the load it serves.

2.3 MITIGATING HIGH AND LOW VOLTAGE WITH AN AVR

Here, we examine system voltage and current for two input voltage cases. The first case is a system delivering power with the voltage 10% high with a 100% load. The second case is a system delivering power at 25% below rated voltage with a 100% load.

2.3.1 CASE 1: SYSTEM VOLTAGE 10% HIGH

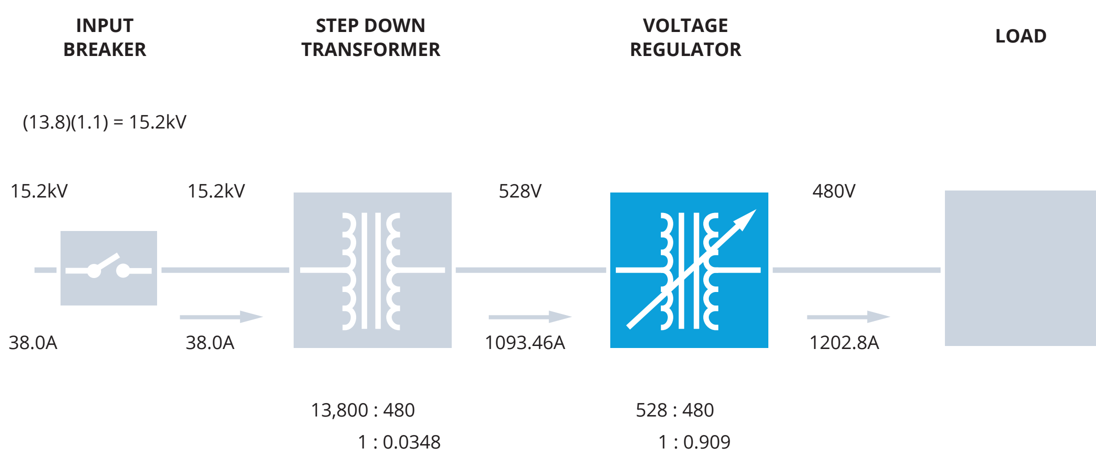

FIGURE 3: Input voltage 10% high. Regulator reduces voltage from 528 to 480.

Figure 3 illustrates voltages and currents on the input and output of each system component.

In this case, it is assumed that the system delivers power with a voltage of 110% of nominal. A 13.8kV nominal system, for example, would have an input voltage of 15.2 kV. Since the load is 1000kVA, the current flowing through the input breaker will be 38.0 amperes. Since the step-down transformer has a fixed turns ratio, the secondary voltage will be 528 volts (rather than 480), and the secondary line current will be 1093.46 amperes.

To address (correct) this issue, the voltage regulator will recognize the higher-than-desired input voltage and adjust its turns ratio accordingly. That means that the regulator's turns ratio will adjust to 1.0 to 0.909 to reduce input voltage to the desired level. The voltage on the regulator's output will be 480 volts, and the current will be the 1202.8 amperes established by the load. Both the step-down transformer and the regulator must be capable of withstanding a voltage of 10% high to manage this issue effectively.

2.3.2 CASE 2: SYSTEM VOLTAGE 25% LOW

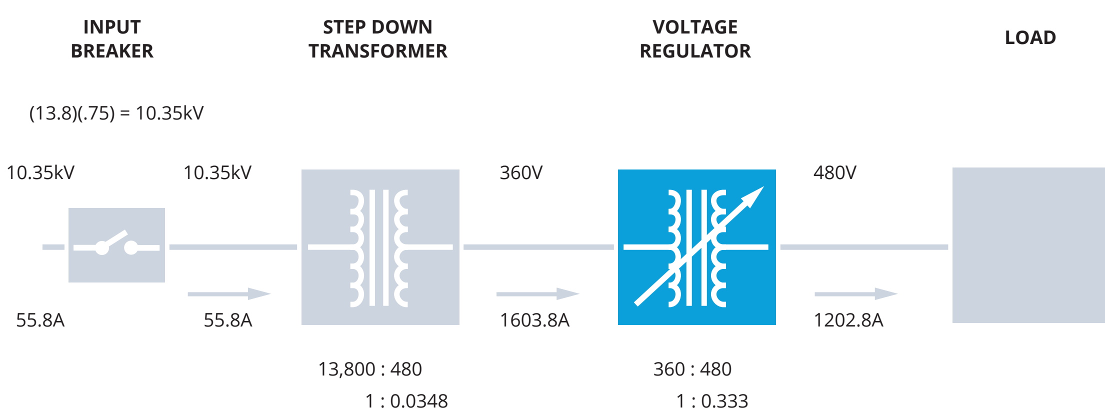

FIGURE 4: Input voltage 25% low. Regulator boosts input voltage from 360V to 480V.

Here we assume that the input voltage is 25% low. For a nominal 13.8kV system supplying a 1000 kVA load, this means that input voltage is 10.35kV with a line current of 55.8 amperes. In this case, the line current is essentially the same as the input breaker rating – a less-than-desirable situation. Since the step-down transformer has a fixed transformation ratio, the low-side voltage will be 360 volts, and the current passing through the low voltage winding will be 1603.8 amperes.

The voltage regulator will address this situation by adjusting its turns ratio to boost the voltage by 33% (a turns ratio of 0.75 to 1.00). For the regulator to adequately address the low-voltage input, the regulator's input winding and the step-down transformer's output winding must be capable of carrying 1603.8 amperes. In other words, the step-down transformer's secondary winding must be capable of conducting 33% more current than its nominal design capability over the duration of the voltage sag.

3. CONCLUSION

When retrofitting an existing system or specifying a step-down transformer for a new system, it is critical to understand the voltage and current demands placed on the step-down transformer – and the overall system – when introducing a voltage regulator. The voltage regulator is often necessary to properly mitigate variation in the system voltage (in this example +10 to -25% voltage). In the previous examples, the step-down transformer was rated at 1000kVA 13.8 kV to 480 with a high-voltage winding designed to carry 41.8 amperes and a low-voltage winding to carry 1202.8 amperes. In Figure 1, this was a perfectly acceptable arrangement based on the assumption that the source voltage was near desired nominal (in this case, 13.8kV). In Figure 3, however, the input voltage was 10% higher than the step-down transformer rating. In Figure 4, the input voltage was 25% low, requiring the step-down transformer's input and output currents to be 33% higher than nominal.

Typically, a transformer can operate reasonably well without long-term damage at 10% over voltage, if we ignore core saturation, higher-than-designed core losses, and high audible noise). A transformer cannot operate, however, for prolonged periods of time with current overloads as high as 33%. In the event of a prolonged overload of 33% or more, there are two acceptable (though not optimal) options:

1) When faced with a voltage sag, limit the load served so that the current requirement does not exceed the step-down transformer rating.
2) Replace the step-down transformer with a unit that can carry the additional current. In the case described previously, the replacement transformer would need to be rated at 1333 kVA.

Transformers are typically specified to ensure that the load they carry will be only 50-75% of their ratings. In our example, the 1000kVA step-down transformer may only be expected to service a 500kVA load. As such, even when the regulator corrects for voltage sags (as shown in Figure 4), the currents passing through the step-down transformer might not exceed its rating. One can often "get away" with this arrangement due to the design margin built into the system. As the system load grows over time, however, the demands on the step-down transformer increase, and a situation that once was acceptable due to over-design is a hidden problem waiting to emerge as a transformer failure.

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