Managing Power System Harmonics for Underground Mines

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Executive Summary

Developing an electrical distribution network for an underground mine has its challenges and integrating new technologies, such as on-demand ventilation or battery-powered vehicles, must be considered at the design stage. Electronic equipment like variable frequency drives and battery chargers are known to generate harmonics, which can negatively affect all mining site installations.

Phase-shifting transformers can be used as part of the development strategy for the mine's power system, as they eliminate some of the harmonics generated by electronic equipment. This is a simple, effective and economic way of limiting power system harmonics, a solution proven time and again in numerous industrial applications.

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Business Challenge

The main electrical distribution network for an underground mine is typically 4.16 kV, 6.6 kV, 11 kV, 12,5 kV, 13.8 kV or even 25 kV for deep and very extensive mines. The choice of voltage is highly dependent on the load level, which is related to the depth and the size of the mine. In Canada, underground mine loads are usually powered by 600 V step-down substations installed at various mine levels. Ventilation usually accounts for most of the load in an underground mine, representing up to 75% of the power used. The other loads come from pumping, mining equipment and service loads.

The power system changes as the mine grows and a 600 V step-down substation is installed at various levels to power these areas. Ventilation needs increase rapidly as the mine deepens and the drifts get longer.

The main ventilation system is installed at the surface or underground and generally consists of two fans of over 500 HP, plus booster fans at each level. The power of each booster fan is typically around 100 HP and many are often needed—it's not unusual to find more than a hundred in a mine.

Booster fan motors can be powered directly with 600 V and ventilation can be controlled mechanically. In such cases, energy efficiency is not optimal and the load power factor is low, around 80% for the entire underground mine. Detuned capacitor banks can be installed right on the 600 V substations or on the medium-voltage mine system to correct the power factor, which will improve voltage regulation and slightly reduce losses in equipment.

Using variable frequency drives (VFDs) to power fans provides perfect ventilation control while optimizing the mine's power efficiency. VFDs are essential for implementing on-demand ventilation in new smart mines (Mining 4.0). The VFD power factor is greater than 95%, which leads to a good overall power factor of 92% to 94% for the underground mine. However, VFDs generate harmonics that can disrupt the operation of certain equipment and impair the quality of the power supply. Harmonics cause losses in equipment and diminish the mine's overall power factor.

VFDs that generate low harmonics (Low harmonics drive) can be used, but these can be very expensive. The equipment is also much larger and generally available for capacities greater than 300 HP. This type of equipment is typically only used for primary ventilation systems. The harmonics can be filtered by tuned passive harmonic filters or by active filters installed right on the 600 V substations or on the medium-voltage system.

Adding harmonic filters (active or passive) has a negative impact on:

- The cost of developing the underground mine
- The size of electrical rooms
- The maintenance costs resulting from additional equipment
- Mine reliability, as this additional equipment can become defective at any time

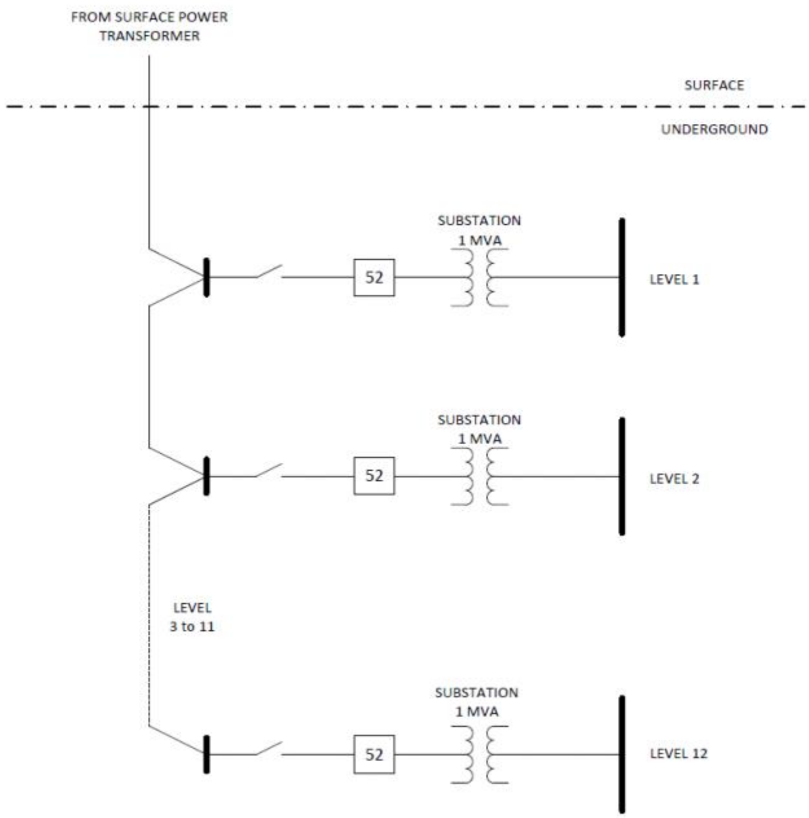
Considering the many substations installed in an underground mine and the wide range of ventilation loads, the harmonics of a medium-voltage system can be reduced without having to add filtering equipment. In this paper, we present a strategy to cancel harmonics by using phase-shifting transformers, which are proven to work and are used in many industrial applications, such as supplying high-power rectifiers, powering multi-pulse VFDs for a mill and other industrial applications.

Ventilation needs may drop in the future when diesel-fueled vehicles are replaced with electrical ones in underground mines. This would require installing battery chargers, known to be a nonlinear load that generates harmonics. Using phase-shifting transformers would also be effective in reducing the harmonics produced by the numerous battery chargers.

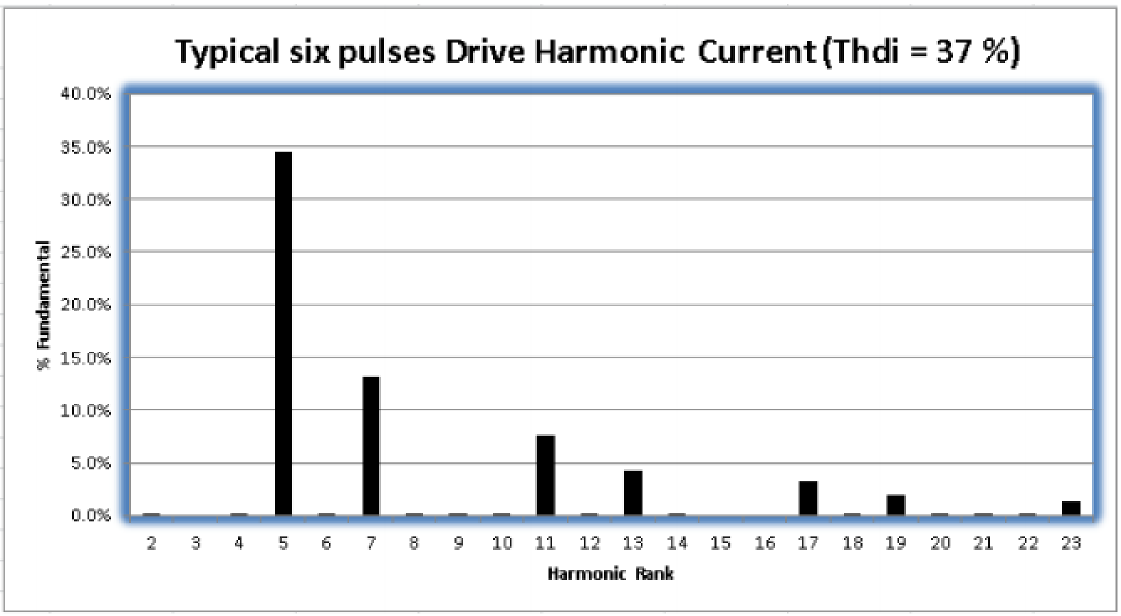
Description of the Solution

The task of configuring a power system for an underground mine is quite similar from one site to the next and involves, at the various mine levels, installing a substation with a standard capacity of 1 to 2 MVA, which lowers the voltage to 600 V and supplies both production and ventilation loads. These loads regularly relocated with the mine's growth and operations. Ventilation is the main load and usually represents about 75% of the overall load for an underground mine. To optimally adjust the ventilation while keeping in mind the system's power efficiency, VFDs are increasingly used for mining applications, primarily for remote sites where the cost of energy is high. Additionally, when the mine is heated, it becomes even more cost-effective to optimize the ventilation in order to bring down heating costs. On-demand ventilation is becoming more prevalent with the advent of new technology and mine digitalization.

Below is the single-line diagram for a typical underground mine system.

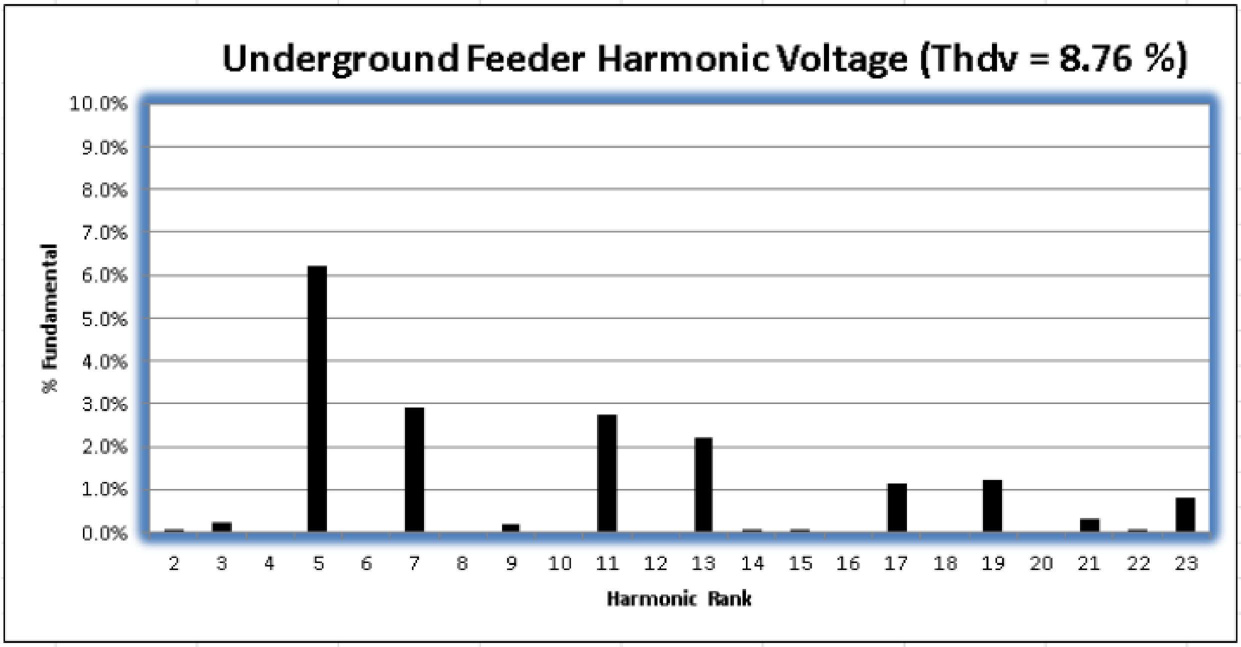


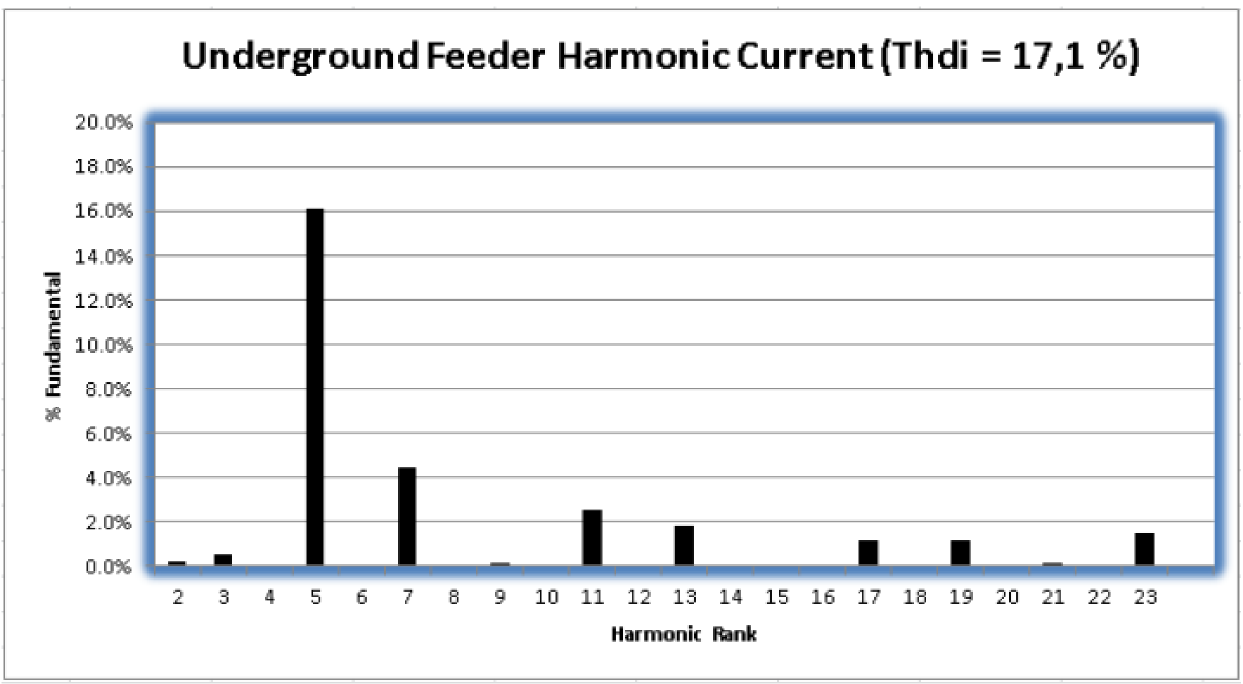
The number of substations tends to increase as the mine expands, and it is common for a few dozen to be installed as years pass. The harmonics generated by VFDs can significantly affect the quality of the power supply for the mining site. The following table shows the harmonics signature of a basic six-pulse VFD with a current distortion rate of over 35%, like those typically used in mines.



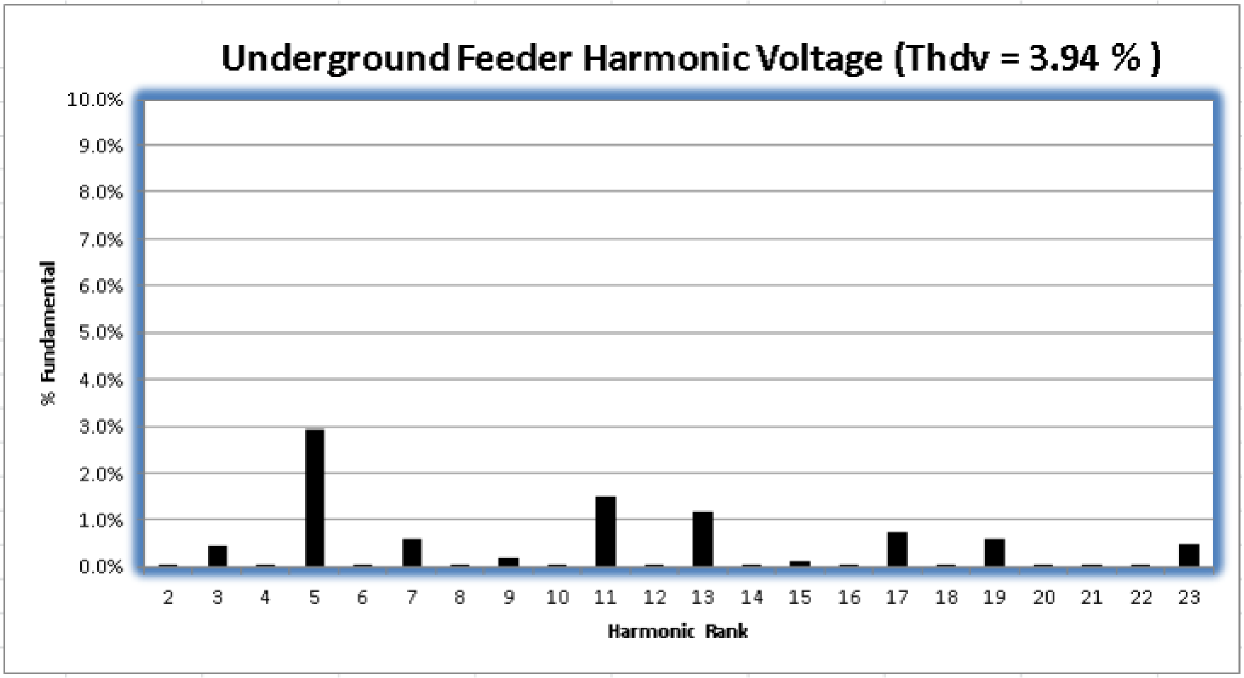
Rank	Freq. (Hz)	Six pulses Drive
1	60	100.0%
2	120	0.0%
3	180	0.0%
4	240	0.0%
5	300	34.5%
6	360	0.0%
7	420	13.2%
8	480	0.0%
9	540	0.2%
10	600	0.0%
11	660	7.6%
12	720	0.0%
13	780	4.3%
14	840	0.0%
15	900	0.0%
16	960	0.0%
17	1020	3.2%
18	1080	0.0%
19	1140	2.0%
20	1200	0.0%
21	1260	0.0%
22	1320	0.0%
23	1380	1.3%

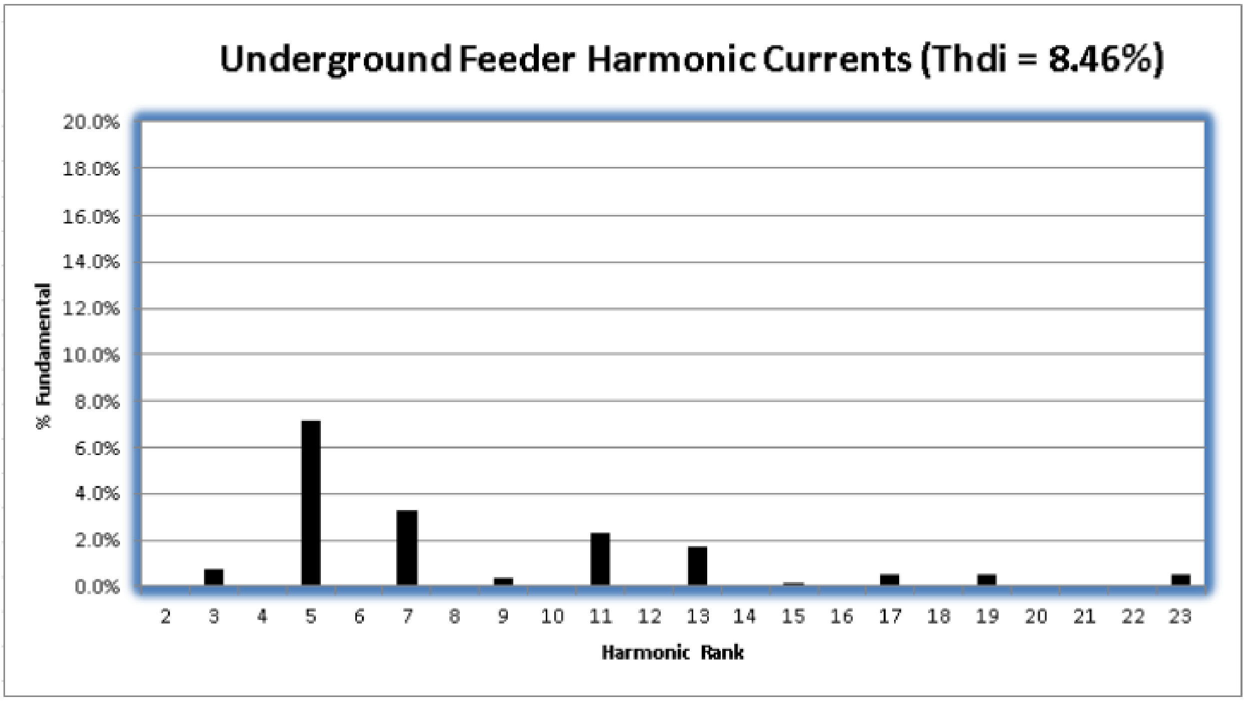
The two following tables show the harmonics measured at the entrance of an underground mine with over twenty-five 13,800/600 V substations, where all ventilation is powered by VFDs without harmonic filters and without phase-shifting between substation transformers.


Underground Feeder Harmonic Voltage (Thdv = 8.76 %)
% Fundamental
10.0%
9.0%
8.0%
7.0%
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Harmonic Rank


Underground Feeder Harmonic Current (Thdi = 17,1 %)
% Fundamental
20.0%
18.0%
16.0%
14.0%
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Harmonic Rank

The tables below show the measurements taken at the entrance of an underground mine with over fifteen 12,500/600 V substations, where all ventilation is powered by VFDs without harmonic filters but using transformers with different phase shifts.





The voltage distortion (Thdv) depends on the source impedance and the harmonics flowing through it.

The two examples in this document are equivalent with respect to the proportion of harmonicgenerating loads. In the first example, the flow of a high level of harmonics triggers extensive voltage distortion, even if the mine is powered by the public utility. The voltage distortion rate for this 13,800 V system exceeds the 5% limit recommended by IEEE 519-2014 – Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq$ 69 kV	3.0	5.0
69 kV < $V \leq$ 161 kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

The second example comes from a remote mine site, powered by diesel generators, and the voltage distortion rate meets IEEE 519 recommendations because the harmonics percentagewise are half those in the first example.

When ventilation loads are properly distributed among the various substations in the underground mine, harmonics can be significantly and efficiently cancelled on a medium-voltage power system, as shown in the second example. The principle is simple: currents from certain harmonic orders are phase-shifted between the substations and cancel themselves out. It is important to select the phase-shifting for each transformer to cancel out the dominant harmonics of the installed equipment.

Benefits of the Solution

The right planning when developing a power system for an underground mine and the selection of optimal equipment will result in a high-performing, safe and reliable system with low harmonics. In fact, using phase-shifting transformers eliminates dominant harmonics without adding equipment. This solution has no impact on mine development costs, as transformers are required for each substation and there is little difference in cost for transformers with different phase shifts.

Additionally, maintenance and operating costs are unaffected because there is no extra equipment and because there is less energy losses caused by harmonics.

Conclusion

Using phase shift transformers can substantially reduce the flow of harmonics current in power systems without affecting the investments and operating costs. This easy-to-implement solution is perfectly suited to the standard electrical distribution network configuration for an underground mine with many small substations.

As a result, using transformers with various phase shifts should be the first alternative considered to reduce harmonics in a growing underground mine. Where necessary,smallercapacity passive or active harmonic filters can be installed at strategic locations to achieve the right level of harmonics for system needs and public utility requirements.

This solution is also efficient in reducing harmonics generated by the use of battery-powered mining vehicles.

About the Author

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Stéphan Landry is an Electrical Engineer with over 25 years of experience in high-, medium- and low-voltage power systems in the energy, mining, and oil and gas sectors, as well as in the pulp and paper industry, data centres and airports. He is recognized for his expertise in off-grid and emergency power systems. His versatility, overall vision and vast field experience acquired during years of performance testing and commissioning are a significant asset in performing feasibility studies, master plans and system design.

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