# VALIDATION OF SIMPLIFIED VARIABLE SPEED CONTROL FOR ROAD TUNNEL JET FANS

[1]Kaito Onoda, [1]Ryoichi Ishizawa, [2]Keigo Hatamoto, [3]Hibiki Sako, [3]Toshiaki Sakaguchi, [4]Alan Vardy
[1]Hanshin Expressway Co., Ltd, JP
[2]Hanshin Expressway Research Institute for Advanced Technology, JP
[3]Sohatsu Systems Laboratory Inc., JP
[4]University of Dundee, Dundee, Scotland, GB

DOI 10.3217/978-3-85125-996-4-07 (CC BY-NC 4.0)


## ABSTRACT

In 2010, the first variable speed control system for tunnel jet fans was installed in the Kobe Nagata Tunnel in Japan. Its purpose was to achieve energy savings in comparison with constant speed control. The original installation, which was based on a 3-level inverter, became due for replacement after more than a decade of successful use. The decision was made to replace it with a system based on a 2-level inverter with the aim of improving space factors, weight, and maintainability. The present paper deals with the entire replacement process that began with the development and verification of the simplified (i.e. 2-level) variable-speed control, followed by validation tests during the migration from the original system. The functionality and effectiveness of the new system are described and future potential is discussed.

*Keywords: jet-fan inverter control, advantages of 2-level inverters, replacement and validation of jet-fan control system*

## 1. INTRODUCTION

In 2009, Nakahori et al [1] confirmed an earlier revelation by Bopp [2] that energy savings in jet-fan operations could be achieved by running groups of jet-fans at a low speed instead of fewer fans at full speed. They compared the performance of 2-level and 3-level inverters and concluded that the superior performance of 3-level inverters would be needed for this purpose despite disadvantages of increased capital costs and space requirements.

In a simultaneous development, described later by Kawabata et al [3], a powerful new noise filter known as a distance free surge absorber ("DFSA") was shown to be capable of greatly reducing all kinds of electrical noise that could be caused by the use of inverters in road tunnels. This opened the door to enabling the use of long distances between the inverters and the jet fans that they were to control and hence avoiding the need to have inverters in the tunnel space.

A combination of 3-level inverters and DFSA was adopted for the control of five (5) jet-fans at the Kobe Nagata Tunnel in 2010, and led to energy savings reported by Kanazawa et al [4]. Since then, more than 130 jet-fans in 15 tunnels in Japan have been operated successfully by the jet-fan inverter control. Furthermore, the use of inverter control outside Japan is receiving increasing interest for similar reasons – e.g. the E4 Tunnel in Stockholm [5].

Developments in inverter technology have now progressed to an extent that makes a compact and lightweight 2-level inverter a potentially standard product for use in tunnel ventilation. To take advantage of this progress, a combination of 2-level inverters and DFSA has been assessed and refined in an extensive development program. Importantly, it has been found that, by increasing the carrier frequency from 5 kHz to 8 kHz, it is possible to use identical DFSA designs for both 3-level and 2-level inverters. This versatility has been verified in full-scale factory tests reported by Sako et al [6] in which 2-level and 3-level inverter control of a jet fan were assessed. In the tests, the noise reduction performance of the 2-level inverter control system was as strong as that for the 3-level inverter system.

The lifetime of the general-purpose inverter for the road tunnel varies from supplier to supplier. The 3-level inverter systems adopted at the Kobe Nagata Tunnel were deemed ready for replacement after more than ten (10) years and the decision was taken to replace it with the newly developed 2-level system. This was done over a period of three (3) years, thereby enabling experience of actual operation to be gained gradually. Most of the remainder of this paper is a description of the whole replacement process at the tunnel including validation tests in a comparative study of the noise-elimination performance of the old and new systems. A summary of future installation plans for inverter control of jet-fans is then given and key conclusions drawn from the paper are summarized.

## 2. INSTALLATION OF INVERTER CONTROL IN THE KOBE NAGATA TUNNEL

### 2.1. Outline of inverter control in the Kobe Nagata Tunnel

The Kobe Nagata Tunnel is 4.0 km long and is located on the Kobe Yamate Line of the Hanshi Expressway No. 31. Figure 1 shows an overview of the tunnel, with the part labelled 'south extension' being added to the original tunnel in December 2010. The concentrated exhaust longitudinal ventilation has three ventilation stations in the tunnel (Hasumiya, Myohoji, and Chuo). The south extension has portal leakage suppression control by the five jet-fans. A comparative study between inverter-based variable-speed control and constant speed control for the jet-fans was conducted at the time of installation [4]. Then, after a period of operation, the *measured* power consumption of inverter-controlled fans was found to be much smaller than that predicted in simulations based on constant-speed control. It was concluded that this is partly because the inverter control has a high rate of operation as the Kobe Nagata Tunnel is located at the center of the Kobe City and conveys more than 20,000 vehicles/day.

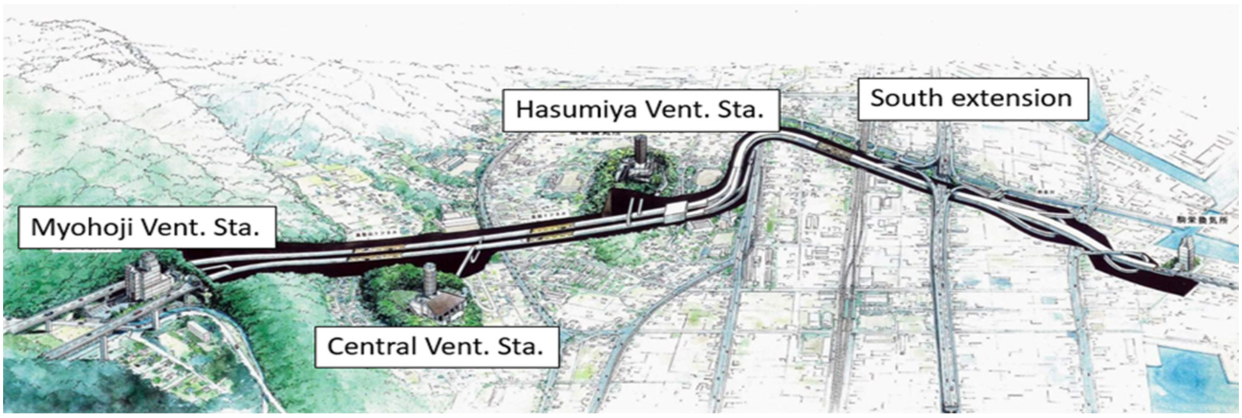


Figure 1: Overview diagram of the Kobe Nagata Tunnel

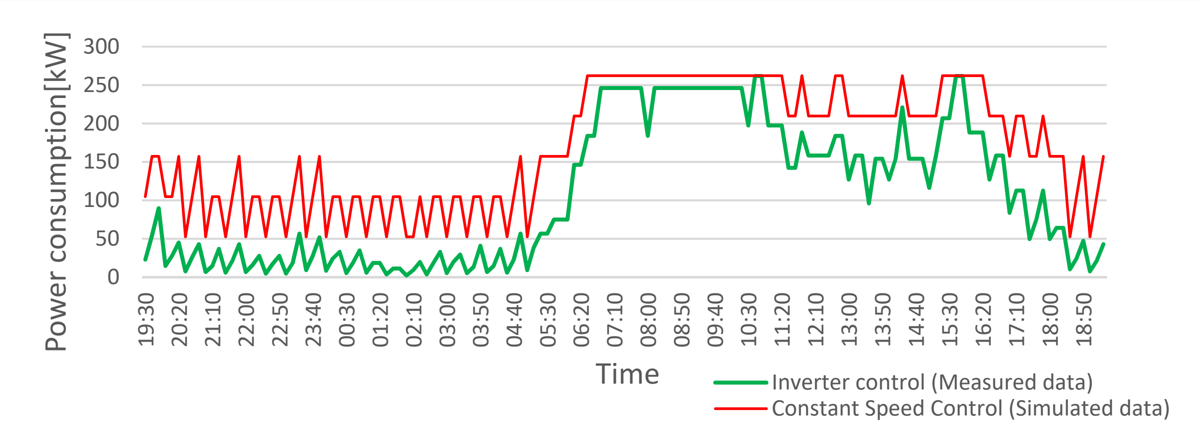


Figure 2: Comparison of power consumption between inverter-based variable and constant speed control

### 2.2. Demands for replacement of inverter control

The industry standard design life of inverters, capacitors and PLCs in the original variable-speed control panels was approximately 10 years, whereas that of the reactor and transformer was at least 20 years. As the time for replacement approached, it was decided to replace only the components with the shorter lifetime such as inverter unit, capacitors and PLC, and to remove damping resistors in the DFSA filter, thereby saving cost and minimizing disruption. This work was carried out in 2020 and the opportunity was taken to take advantage of progress in the development of a simplified control system using 2-level inverters instead of the original 3-level inverters.

## 3. REPLACEMENT OF INVERTER CONTROL IN THE KOBE NAGATA TUNNEL

### 3.1. Verification of the simplified variable-speed control

Table 1 gives a comparison of the 3-level and 2-level inverters. It shows that 2-level inverters have important advantages over 3-level ones

Additionally:

- 2-level inverters excel in size, weight, and efficiency.
- The carrier frequency in 2-level inverter can be up to 8 kHz, whereas that for 3-level inverters is 5 kHz. This has the additional benefit of enabling the DFSA filter to be smaller than is required for 3-level inverters.

The acceptability of electrical noise generated by 2-level inverters has already been verified in factory tests [6]. However, it was considered necessary to validate it in actual tunnel tests.

Table 1: Comparison between 3-level and 2-level inverter of 50 kW

| Items | 3-level inverter | 2-level inverter |
|---|---|---|
| Width x Depth x Height | 450×348×725 mm | 264×335×543 mm |
| Weight | 90 kg | 39 kg |
| Efficiency | ～97% | ～98% |
| Carrier frequency | Up to 5 kHz | Up to 8 kHz |

### 3.2. Validation test of the simplified inverter control prototype

The factory tests [6] clarified the magnitude of the zero-phase current, the prime source of noise. They showed that little difference exists between the performance of the two types of inverters when DFSA filters are used. The zero-phase current, however, varies depending on many factors such as power cable length, power cable type, electrical power receiving/transforming equipment, grounding circuit, inverter operating frequency, and jet-fan motor characteristics. Therefore, a test to compare the zero-phase current of the existing 3-level inverter control and the new simplified inverter control prototype was conducted with the jet-fan #1 which is controlled with the longest cable of 800 m from the control room.

Figure 3: Prototype control

The power cable for the jet-fan #1 was disconnected from the existing 3-level inverter control panel and temporarily connected to the 2-level prototype control panel shown in Figure 3 to conduct a validation test. The zero-phase currents of the two inverter controls were measured at 20, 30, 40, 50 and 60 Hz of the power frequency with the results shown in Figure 4. The zero-phase current of the 2-level inverter control indicated a larger magnitude than 3-level control in the lower frequency region such as 20, 30, and 40 Hz. The reasons of the large magnitude are considered due to the operating principles which differ in the 2-level and 3-level inverter such as the pulse amplitude and modulation method. A trial was tested to see an impact of increasing the zero-phase inductance by adding one more reactor on the zero-phase current. As expected, the zero-phase current became smaller as is shown in Figure 4. It has been confirmed that enhancing the zero-phase reactor (using two reactors for example) reduces the zero-phase current. The zero-phase current of the prototype control was the maximum of 220 mA at 20 Hz with the simplified design. This is far smaller than 1,000 mA which is considered as the acceptable upper limit of the zero-phase current [7]. Accordingly, it was decided that no enhancement of Lz (zero-phase reactor) was required in the DFSA filter.

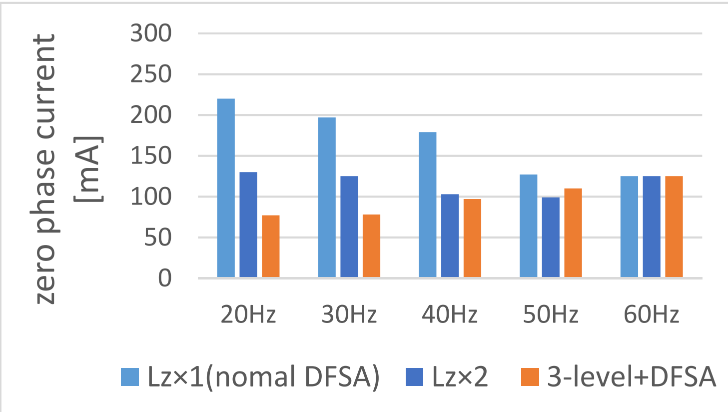


Figure 4: Comparison of zero-phase currents when zero-phase reactor is

### 3.3. Validation test with one unit of the simplified speed control

After installation, a long-term test (> a year) of the simplified inverter control system was conducted to assess the approach of replacing major parts of the inverter panel instead of the entire panel. Jet-fan #1 was selected for this purpose. The inverter unit, capacitor, PLC unit and other miscellaneous parts of the existing inverter control for the jet-fan #1 were replaced. Figure 5, 6 and 7 show the replacement of the inverter unit and illustrate the potential for reduction in the size of future control panels. This can be important when (as usual) space in control rooms is at a premium.

Figure 5: 3-level inverter unit in the control

Figure 6: Exchanging the inverter unit

Figure 7: 2-level inverter unit installed in the control

During this test period, the inverter controls for jet-fans #2, #3, #4 and #5 remained as before. All five (5) inverter controls were operated through the existing PLC for 3-level inverters and, to enable this, an additional "PLC for conversion" was installed to pass the control signals to the 2-level inverter. The replaced 3-level inverter unit was held on standby in case of any need to respond urgently to an emergency. The system configuration for this long-term reliability test was shown in Figure 8. As expected, all five jet-fans operated interconnectedly without any issues throughout one year period of the long-term reliability test and no electrical noise troubles were caused by the new simplified inverter control.

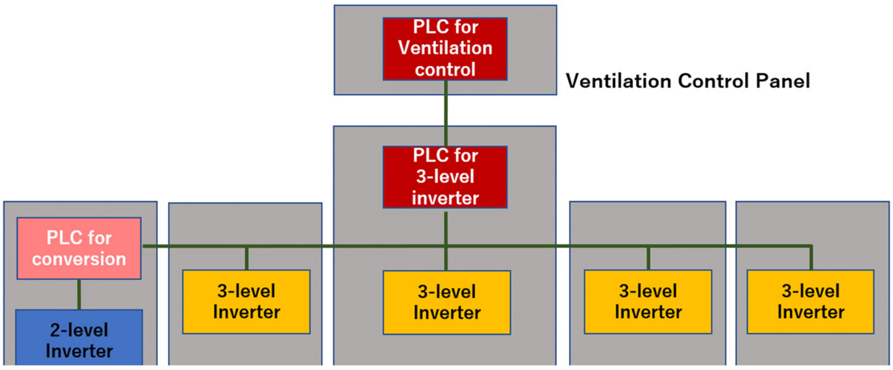


Figure 8: Control system including added "PLC for conversion"

### 3.4. Validation test with complete replacement

Following the success of the test for the inverter panel #1, the remaining four inverter panels were upgraded using the same approach for parts replacement. To minimize the total cost of construction and operation, this was carried out in two stages, in each of which two panels were upgraded. In addition, the interconnecting control PLC unit for 3-level inverter was replaced with a new one due to it reaching the end of its design life.

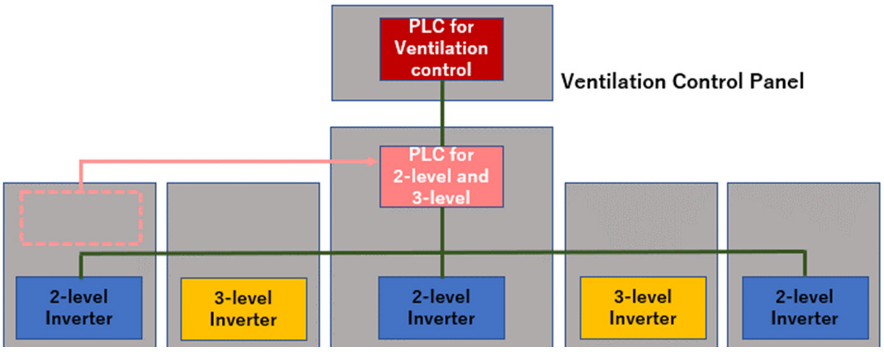


Figure 9: Inverter control system at the Stage 1 of replacement

Stage 1: In the first stage, the control software for the 3-level and 2-level inverters was installed in the "PLC for conversion" that already controlled jet fan #1, and the old interconnecting PLC was replaced by the "PLC for conversion". The relevant components of the two inverter panels #3 and #5 were replaced to make them simplified inverter controls. The operation of the new interconnecting "PLC for conversion" with 2-level and 3-level software, and three 2-level and two 3-level inverter controls were confirmed by measuring the electrical parameters of voltage and current. The whole inverter control system then resumed normal operation. Figure 9 illustrates the control system configuration at the end of Stage 1.

Stage 2:
After a short period allowed to confirm that everything was operating correctly, inverter panels #2 and #4 were replaced in the same manner as above. This completed the migration from 3-level to 2-level and, as a final step, the "PLC for conversion" loaded the software for the 2-level inverters, replacing the 3-level software. Figure 10 illustrates the control system configuration at the end of Stage 2. The operation of the new interconnecting PLC for 2-level inverters, and five 2-level inverter controls was confirmed by measuring the electrical parameters of voltage and current and the whole inverter control system again resumed normal operation.

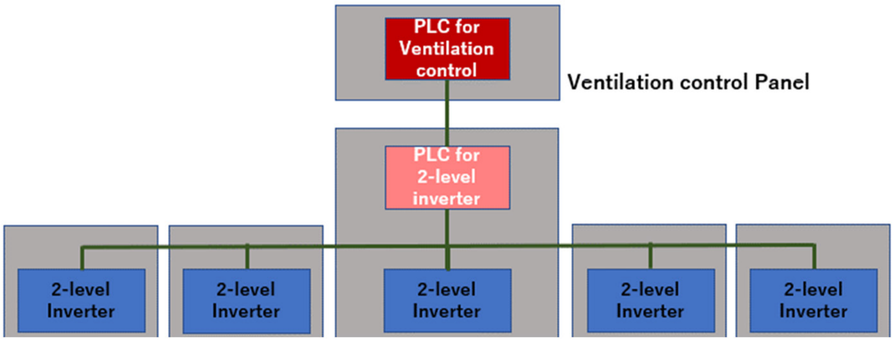


Figure 10: Inverter control system at the Stage 2 of replacement

### 3.5. Comparison of the 3-level and 2-level inverter controls

(1) Efficiency of the inverter control

So far, the performance of the control system has been discussed primarily with a focus on stability and the suppression of unacceptable electrical effects. However, the power efficiency of the inverter units is also important. Accordingly, this was measured at jet fan #1, giving results shown in Figure 11. The figure compares the 2-level performance with that of the 3-level inverters before their replacement and, for this purpose, 'efficiency' is defined as the ratio of output power to input power. By inspection, the new 2-level units actually outperformed the original 3-level ones, albeit by only about 2% over the range used in practical operation. Somewhat greater improvement (approximately 8%) was obtained at a frequency of 20 Hz, but the absolute efficiencies are then smaller than at higher frequencies.

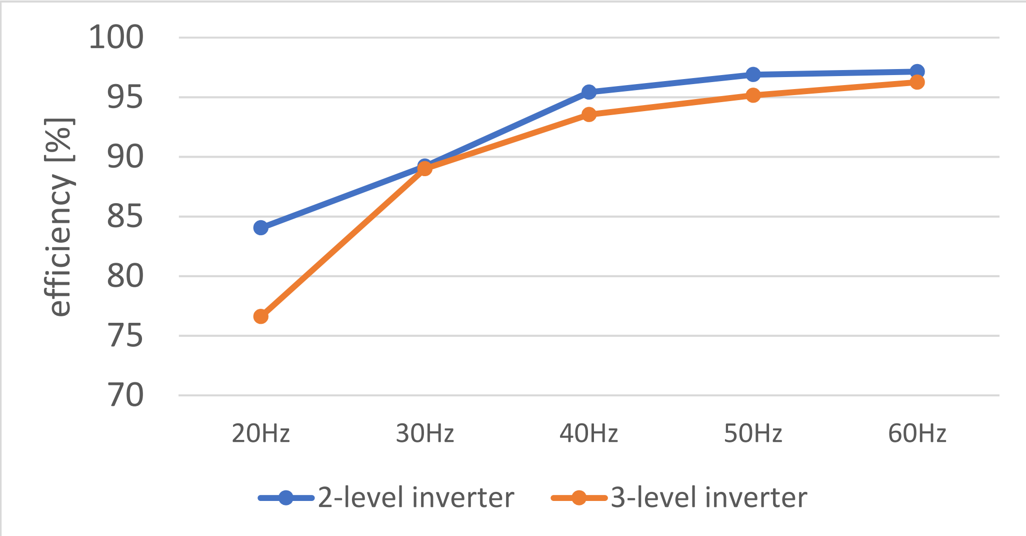


Figure 11: Comparison of 2-level and 3-level inverter control efficiency

(2) Zero-phase current

It is well known that various forms of electrical noise caused by inverters can have negative effects on the operation of jet-fan motors and other tunnel devices such as AM radio, sensors, and communication equipment. The standard LC filter is effective in reducing the surge voltage, but it does not restrict the zero-phase current. In contrast, the DFSA filter [3] does limit the zero-phase current and it performs better than various other types of filters assessed by Weicker et al [7],

Measurements of the zero-phase current at jet fan #1 have been described in Section 3.2, in which it is shown that the values for the 2-level unit are greater than those for the 3-level unit, but nevertheless far smaller than the acceptability limit of 1000 mA. Corresponding measurements for all five jet fans are shown in Table-2. It is seen that the current increases with increasing cable length. This is to be expected but, importantly, it may be inferred that the use of significantly greater cable lengths would also be acceptable. For completeness, this expectation is assessed in Figure 12, which shows maximum zero-phase currents measured in 15 tunnels in Japan in which inverter-driven speed control is used for jet-fans. Figure 12 shows a clear dependence on tunnel length and it also shows that, for the 3-level inverters, the dependence tends to reduce with increasing length. The measurements for the 2-level inverters in the Kobe Nagata Tunnel are at the upper end of the range of measurements for 3-level inverters, but it is too early to know whether their dependence on cable length will also begin to reduce with increasing length.

Table 2: Maximum value of the zero-phase current of the inverter control at the Kobe Nagata Tunnel

| | Jet fan#1 | Jet fan#2 | Jet fan#3 | Jet fan#4 | Jet fan#5 |
|---|---|---|---|---|---|
| Cable length(m) | 800 | 800 | 650 | 650 | 500 |
| Zero phase current(mA) 3-level inverter | 125 | 110 | 98 | 91 | 77 |
| Zero-phase current(mA) 2-level inverter | 220 | 201 | 174 | 134 | 133 |

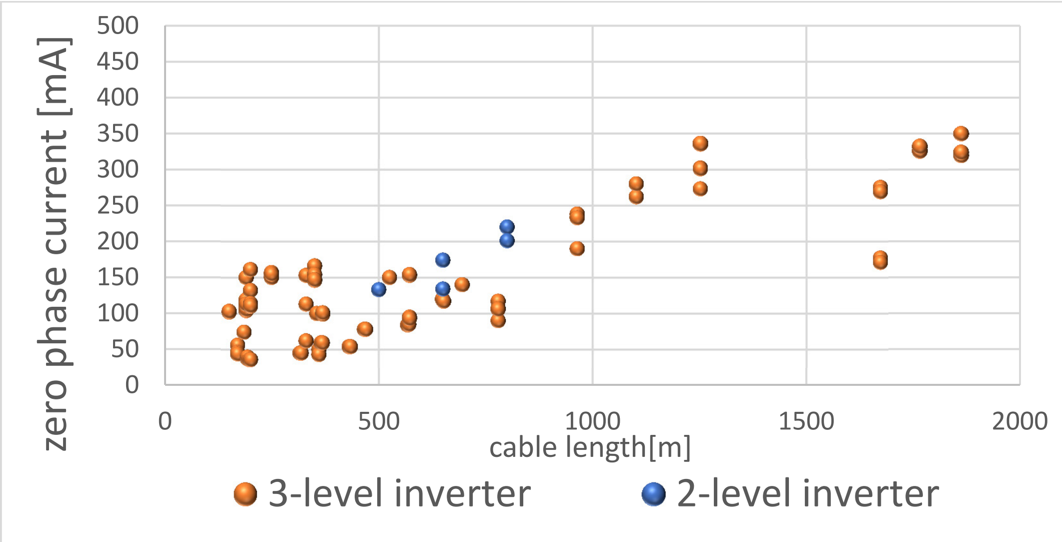


Figure 12: Correlation between cable length and maximum zero-phase current

## 4. NEXT STEPS TOWARD WIDER INSTALLATION

Tunnel operators and designers must consider financial cost as well as efficiency even in times when climate change demands ever-increasing attention. For these purposes, it is necessary to acknowledge that the initial capital cost of inverter control systems exceeds that of constant-speed systems. It is therefore of considerable interest to predict life-cycle costs that include both capital and operational costs. Such a study has been undertaken to predict life-cycle costs for the proposed replacement of 3-level control by 2-level control in the Shorenjigawa Tunnel in Japan. Figure 13 shows predicted total life-cycle cost in twenty years for 34 fans including (i) initial construction and installation, and parts replacement at the end of ten years of operation, (ii) electrical power requirements and (iii) maintenance. This shows that a break-even point occurs after about half of the design life of inverter units (and hence about a quarter of that of other components). Furthermore, it is to be expected that the longevity of jet-fans and their motors will be greater in the variable-speed mode. Thus, the increased flexibility of variable-speed control – in response to incidents as well as in routine operation – is achieved simultaneously with reduced life-cycle costs and reduced detriment to the environment. None of these benefits is game-changing, but their potential collective influence is nevertheless compelling.

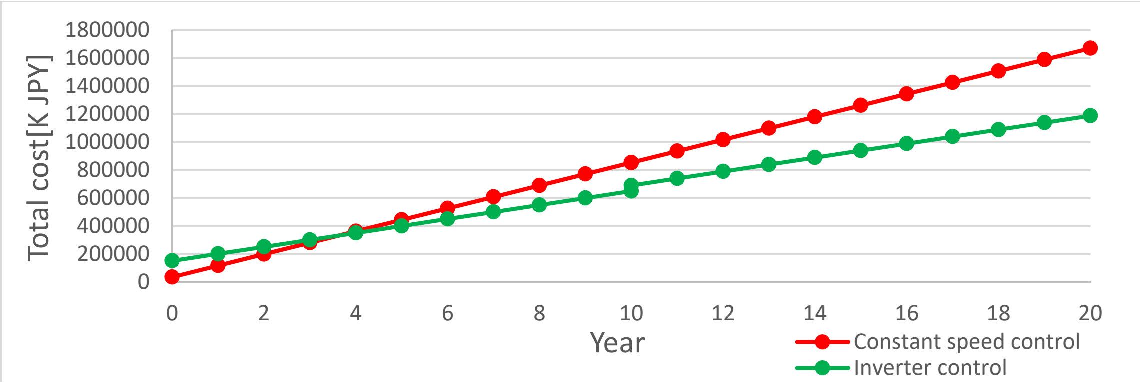


Figure 13: Comparison of Life-Cycle Cost between inverter control and constant speed control at the Shorenjigawa Tunnel

## 5. CONCLUSION

The paper has assessed the practical potential of using 2-level inverter speed-control for tunnel jet-fans instead of 3-level control, thereby reducing costs and also reducing space demands in control rooms. Inevitably, to enable the assessment to be made on the basis of actual measurements, it has been necessary to focus on a particular tunnel in which direct comparisons could be made. However, the inferences drawn from the measurements have been interpreted generically. Particular attention has been given to assessing electrical noise such as zero-phase current that is strongly-dependent on the method of filtering the inverter output. It has been shown that, when used in conjunction with DFSA filters, the zero-phase current caused by 2-level control exceeds that for 3-level control, but is nevertheless far below acceptability limits even with cable lengths as large as 800 m. It has also been shown that power efficiencies in the desired frequency range are similar for both methods. Furthermore, it has been shown that life-cycle costs of inverter-driven control of jet fans is significantly smaller than that of constant-speed systems even though the initial capital costs are greater.

## 6. REFERENCES


[1] I Nakahori, T Ato, K Murakami, D Araki, T Kanatani, A Vardy, "The use of inverter-driven jet-fans to reduce tunnel ventilation costs", BHR Group, 13th ISAVVT, pp69-80, 2009.

[2] R Bopp, "Energy-optimized ventilation of road tunnels by speed control of jet fans", *Proc 1st int conf on Tunnel Control and Communication, Basel Switzerland*, ITC Ltd, 219-229, 1992.

[3] T Kawabata, I Nakahori, "Variable speed driving equipment for the jet-fan induction motors in road tunnel", Japan Patent No. 5300775, registered on June 26, 2013.

[4] K Kanazawa, H Hara, A Tsurumaki, H Fujimoto, H Kurano, I Nakahori, T Ato, "Application of inverter-driven jet-fans to the Kobe Nagata Tunnel", BHR Group, 14th ISAVT, pp91-102, 2011.

[5] R Brandt, S Lucchini, "Ventilation of the E4 Stockholm Bypass", Conference Proceedings on 16th Australasian Tunneling Conference, Sydney, Australia, 2017.

[6] H Sako, T Sakaguchi, S Abe, A Vardy, "A strong advance in variable-speed control of road tunnel jet fans", BHR Group, 20th ISAVFT, Brighton, UK, pp389-40, 2022.

[7] M Weicker, G Bello, D Kampen, A Binder, "Influence of system parameters in variable speed AC-induction motor drives on parasitic bearing currents", EPE'20, ECCE Europe, pp1-10, 2020.