Mitigation of EMI in High Voltage Substation Environment by use of Wiring cables with Improved Screening Effectiveness

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Abstract - **In order to demonstrate the shielding effectiveness of the improved signalling cable the paper presents, firstly, the design of the screening of a cable and the results of laboratory measurement on the low frequency (50 Hz to 10 kHz) screening. The screening effectiveness for signalling cables of traditional structure and that of improved design has been compared by real scale site tests. For this purposes the cables of both constructions have been installed along identical routes in the switchyard of an open air 220kV/120kV/20kV substation. The interference levels transferred into the common mode loop of the tested cables has been measured by the following EMI sources:**

- **current injection into the earthing grid at 50Hz,**
- **switching of a bus-bar by disconnector,**
- **injection of damped oscillatory wave (1MHz)**
- **injection of electrical fast transient/ burst (5/50ns).**

The results of tests and the conclusions on the shielding performance of the improved sheath structures are described.

Keywords: wiring cable, shielding effectiveness, shielding design, damped oscillatory wave, fast transient/burst

I. INTRODUCTION

In a substation environment, the risky interference to automation, control and relay protection apparatus composed of sensitive electronic - especially microprocessor - components, is, in the most cases, generated in the cables between apparatus at different locations, i.e. control room, relay house or HV equipment at different points of a switchyard [1, 2]. The application of fibre optical cables is an excellent mitigation against EMI in HV substation. There are, however, functions where the copper cable can not be replaced by fibre optical one's, e.g. control of circuit breakers, connections to voltage and current transformers, power feeding. In that cases, the signalling cables with improved shielding effectiveness mitigate both ground potential rise at power frequency and high frequency EMI. This papers describes recent development of signalling cable with such improved shielding.

The metallic structure of the sheath of signalling cables, normally used in Hungary, is composed of only a double layer armouring of helical winded thin (0.1 mm each) steel tapes. This sheath structure has two drawbacks, i.e. poor shielding (screening factor of about 0.95) at low frequency and difficulties in reliable sheath bonding or earthing. Both drawbacks have been eliminated with two modifications by a new design of the sheath. Firstly, an additional concentric copper wire shield with contact helix has been applied. With this structure the reachable screening factor can be controlled in a very flexible way with the appropriate design of the conductivity (cross-sectional area) of the shield. For the bonding of the shield the same reliable technology is applicable as normally used for stranded conductors. Secondly, the thickness of the steel tape has been optimised accordingly to the screening factor required for power frequency compensation.

Four types of experimental cable, with the improved shielding, have been designed and a production length has been manufactured from each.

II. SHEATH DESIGN

The following basic expression for the screening factor has been applied for design of new screen structure [3]:

$$k=\frac{Z_I}{Z_0+Z_E}=\frac{R_S}{R_S+\left[-R_p(I_S,\omega)+jX_p(I_S,\omega)\right]+Z_E(\rho,\omega)}$$

Controllable quantities in the design:

- R_s d.c. resistance of the sheath
  - cross section area of the screen
  - filling/gap rate of wire screen
- Z_A additional impedance of the steel tape armour
  - cross section area of the armour:
  - number of layers (2)
  - thickness of the tape.

It should be noted that Z_A is a function of the magnetic field strength in it, thus the current flowing in the sheath.

A. Sheath structure

Regarding the structure of the experimental cable with new design (Fig. 1) the following options have been considered:

- screen:
  - * concentric helically applied round copper wires, options:
    filled screen or gapped screen
  - * with contact helix copper tape
- Double steel tape armour options of tape thickness:
  v = 0.2 mm or v = 0.5 mm

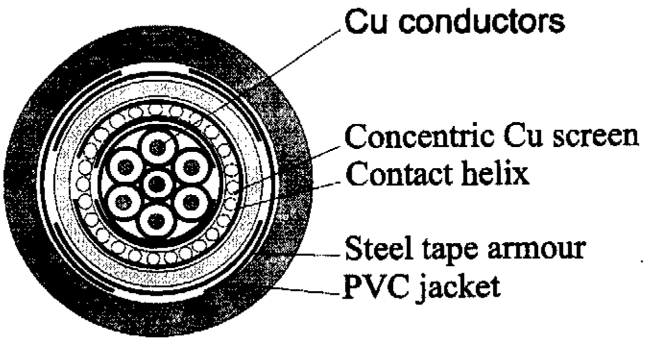


Fig.1 - Sheath Structure of the Experimental Cables with New Design

B. Parameter identification

To allow the evaluation of the screening factor of the sheath with new designed the following parameters are identified:

(1) Screen resistance identification

The resistance of the wire screen are identified:

- for cross sections determined by:
  - core diameters to selected structures:
    30x1.5, 14x1.5, 4x2.5
  - arrangement of the concentric wire screen
    - filled screen (Type: **fil**)
    - gapped screen (Type: **gap**)

(2) Additional impedance identification

The additional impedance due to the steel armour are identified:

- for designed amour characterised by:
  - armour diameters to selected core structures:
    30x1.5, 14x1 and 4x2.5
  - steel tape thickness:
    v = 0.2 mm v = 0.5 mm.

This identification has been made on the bases of measurements performed previously on steel tapes of identical materials [3].

C. Evaluation of the screening factors

Using these evaluated parameters the expected screening factors are obtained for the designed cable structures by the application of the above basic formula. The results are plotted in Fig. 2.

It is easy to verify that the curves of screening factors are separated in two groups. The screening factors related to the filled screened (the curves marked by solid lines) are lower (better) for all studied cases than the one's related to the gapped screen (Marked by dotted lines). It means that there is a significant improvement in the screening factor when comparing the filled screen with the gapped one. It is due to the lower d.c. resistance of the filled screen.

It can also be seen that the screening factor is - of course - improved by the increase in the thickness of the steel tape armour. In addition, the screening factors are varying with the current in the screen due to the current dependent additional impedance Z_A.

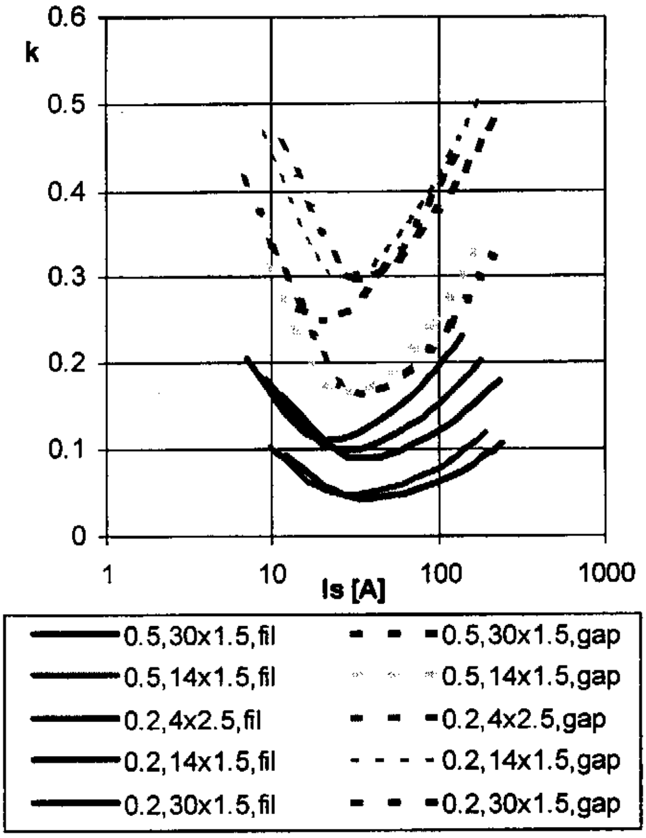


Fig. 2 - Evaluated screening factor of the cable with new design

III. LABORATORY MEASUREMENTS

The following shielding characteristics of the experimental cables with new design has been determined versus the current, at 50 Hz:

- measured: internal and external surface impedance
- evaluated: transfer and total screening factors

The same quantities have also been measured versus the frequency, up to 10 kHz, using the biasing current of 50 Hz, as parameter.

A survey of the results of laboratory measurements is plotted in Table 1. For screen characterisation of, firstly, the d.c. resistance of the screen are plotted. The screening factors relevant to 50 Hz are listed both for low sheath currents (5 As) and at that current where the minimum values occur. Above that current the screening factor increases again due to the saturation if the steel armour. The screening factors are improving with the decrease of the d.c. resistance. When considering frequency dependence of the screening factor a monotonous decrease can be verified with increasing frequency (compare the values for 50 Hz and 10 kHz given in the Tab. 1)., An opposite tendency should, however, be noted, i.e. higher (worth) screening factors are relevant to lower d.c. resistance's, involved in cables with higher diameters. The worthiness of the screening factor is caused by the inductance contribution to the internal surface impedance due to the spiralling of the wire sheath.

Table 1 - D.C. resistance and screening factors of the cable with new design

Cable type		d.c. res.	Screening factor		
			50 Hz		*10 kHz*
core	screen	Ω/km	Start. value I_s=5A	Min. value	
30x1.5	filled	0.165	0.110	0.029	0.0026
14x1.5	filled	0.219	0.141	0.045	0.0019
4x2.5	filled	0.320	0.186	0.054	0.0007
14x1.5	gap	0.775	0.440	0.154	0.0028

IV. MEASUREMENTS IN SUBSTATION ENVIRONMENT

A. Test arrangement

For comparison purposes the cables of both traditional and new construction have been installed along identical routes in the switchyard of an open air 220kV / 120kV / 20kV substation. Test configuration, i.e. lay out and the circuits formed by measured cables are shown in the Fig. 3 and Fig 4, respectively.

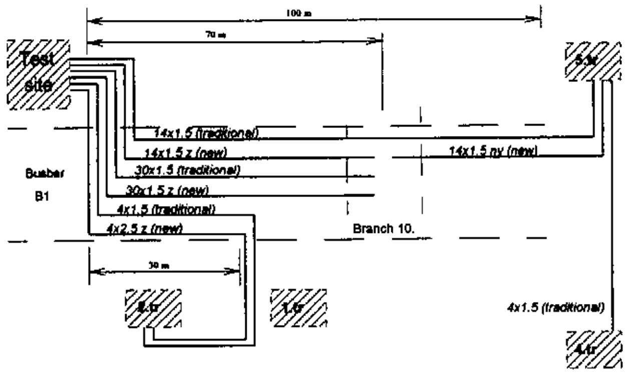


Fig. 3 - Lay out of the measured signalling cables

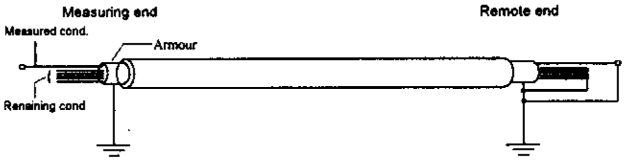
B. Applied test waves

On the course of the field tests the cables have been excited by the following type of test waves: 50 Hz current injection, HV switching by isolator, injection of damped oscillatory wave and electrical fast transients/burst.

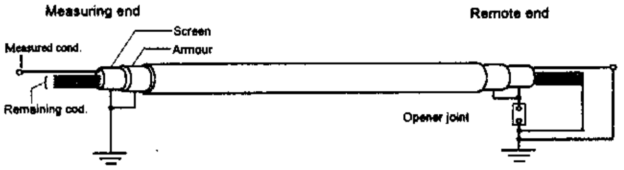
(1) 50 Hz current injection

The 50 Hz current has been injected by one phase out at the 120 kV side of the 220 kV / 120 kV transformer (no 5).

The majority of the total zero sequence current ($3I_o$) is injected into the earth grid through the neutral of the transformer no 5 (see Tab. 2).



a) Traditional type of screen



b) Screen with new design

Fig. 4 - Bonding and earthing of the conductors and the screen

Table 2 - Current magnitudes injected at 50 Hz:

Screen of new cable	Currents in the neutral of transformers [A] ∠phase				Total current [A] ∠phase
	1. tr	*2. tr*	*4. tr*	*5. tr*	*$3 I_0$*
OPEN	105 ∠-17°	22 ∠-45°	0 ∠0°	590 ∠-13°	713 ∠0°
CLOSED	96 ∠-10°	26 ∠-160°	0 ∠0°	524 ∠-148	676 ∠0°

Current of significant magnitudes have been measured in the screen of the cable with new design, especially in that, the remote end of which is in the close vicinity of the transformer no 5 (Tab. 3). In case of a phase-to-earth fault even 10 times higher current may be injected into the grid than the current applied under the test. Consequently, the current in the sheath may overtake even 400 A which requires high enough cross-sectional area, reliable continuity and earthing of the screen.

Table 3 - Currents on screen the new cable (50 Hz):

Core type	14x1.5 fil	30x1.5 fil	4x2.5 fil	14x1.5 gap
Current [A]	14.1	13.3	7.9	40

The variations of the conditions on the screen to earth path applied during the measurements of the common mode voltages are shown in Tab. 4.

Table 4 - Measured longitudinal voltages (50 Hz):

Measured cable	Screen condition of new cable	
	open	*closed*
New	$U_N(0)$	$U_N(1)$
Traditional	$U_T(0)$	$U_T(1)$

Table 5 - Measured common mode voltages at 50 Hz

Relation	Cable type						
	New design				*Traditional*		
	Type of		Voltage [V] with screen		Type of	Voltage [V] with screen of new cable	
	core	*screen*	*open* $U_N(0)$	*closed* $U_N(1)$	*core*	*open* $U_T(0)$	*closed* $U_T(1)$
Test site - - Branch 10	30x1.5	filled	4.7	0.25	30x1.5	4.8	3
	14x1.5	filled	4.8	0.14	-	-	-
Test site - - Branch 10 - - Tr.5	14x1.5	filled	22	-	14x1.5	20.5	16.9
	14x1.5	gapped					
Test site - Tr.2	4x2.5	filled	0.9	0.26	4x2.5	0.9	1.24
Branch 10 - Tr.5	14x1.5	gapped	17.7	2.5	-	-	-

Table 6 - Screening factors at 50 Hz

Relation	Cable type						
	New design				*Traditional*		
	Type of		Screening factor		Type of	Screening factor with screen of new cable	
	core	*screen*	*at test site*	*laboratory*	*core*	*open*	*closed*
Test site - - Branch 10	30x1.5	filled	0.056	0.055	30x1.5	1.02	0.625
	14x1.5	filled	0.031	0.065	-	-	-
Test site - - Branch 10 - - Tr.5	14x1.5	filled	-	-	14x1.5	0.932	0.824
	14x1.5	gapped					
Test site - Tr.2	4x2.5	filled	0.149	0.154	4x2.5	1	1.37
Branch 10 - Tr.5	14x1.5	gapped	0.305	0.186	-	-	-

The common mode voltages caused by the 50 Hz current injection are plotted for the different relations and screen conditions in Tab. 5. From that common mode voltages the following screening factors have been derived:

- screening factor for the new and traditional cables:

$$k_N = \frac{U_N(1)}{U_N(0)} \text{ and } k_T(0) = \frac{U_T(0)}{U_T(0)}$$

- screening factor for the traditional cables improved by the compensating effect of new cables:

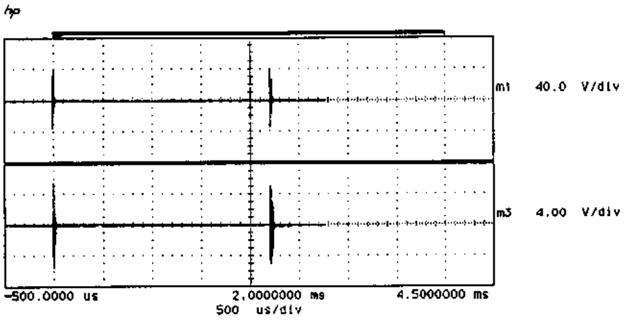
$$k_T(1) = \frac{U_T(1)}{U_N(0)}$$

The results on the screening factors obtained from the site tests and the relevant values of the laboratory measurements are plotted in Tab. 6. The screening factors of the new cable measured on the site are in good agreement with that of measured in laboratory. The improvement in the screening factor of the traditional cable due to the presence of the new cables is better than the screening factor of the screen itself.

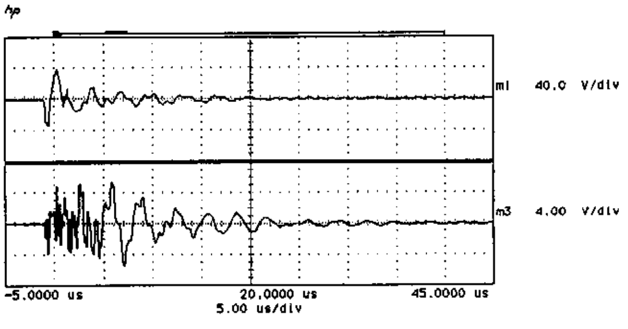
(2) Transients due to switching operation

During this test one unloaded bus-bar (B1) of the double bus system has been repeatedly switched off and on by isolator (disconnecting) switch. For comparison purposes the switching transients generated in the common mode paths of the test cables have been recorded simultaneously by a dual channel digital oscilloscope with 1 GHz sampling. The core structures of the compared traditional and new cables are identified in the Tab.7. The measurements were performed with screens earthed at both ends. In addition comparisons were made for the conditions when the screen of the traditional cable was earthed at both ends while the screen of new cable was earthed at one (remote) end only.

As an example, the time functions of the common mode voltages recorded in the 30x1.5 type traditional (upper wave) and new (lower wave) cables are shown in Fig. 5. For the sake of completeness the wave shape of the induced transient voltages are reproduced by the use of two different time scales. The time scale of 500 µs/div allows the identification of the repetition time of the transients (Fig.5a), while the 5 µs/div scaling (Fig.5b) provides better resolution thus allowing the estimation of the frequency of the damping oscillatory wave.



a) time scale: 500 µs/div



b) time scale: 5 µs/div

Upper wave: traditional 30x1.5 cable
Lower wave: new, filled screened 30x1.5 cable

Fig. 5 - Common mode voltages due to switching off by HV isolator

The shielding effectiveness of the new screen can easily be verified on the bases of the ratios plotted for the maximum amplitudes of the damped oscillatory waves in Tab. 7.

Table 7 - Typical common mode voltage ratios of maximum amplitudes for new and traditional cables

Screen type		Voltage ratio
Traditional (upper wave)	New (lower wave)	New . Traditional
30x1.5	30x1.5 fil.	0.16
14x1.5	14x1.5 fil+gap	0.5
4x1.5	4x2.5 fil.	0.1
30x1.5)	14x1.5 fil.	0.17

Considering the waveform characteristics, the typical frequency of the damped oscillatory wave ranges between 270-340 kHz (ideal frequency accordingly to f_o = $C/4l$ would be 625 kHz). The repetition rate is about 2.5 mHz (400 Hz), which is practically identical with the one specified in the relevant standard [4].

(3) Injection by test generators

To check the shielding effectiveness of the screen with well defined standardized waves and in very high frequency range disturbing signals have been injected into the sheath-to-earth loop accordingly to Fig. 6.

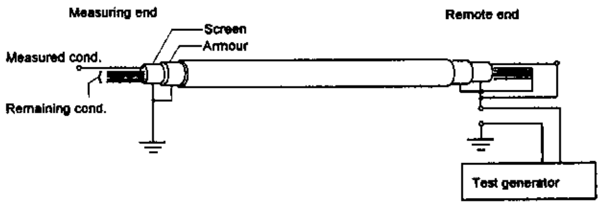


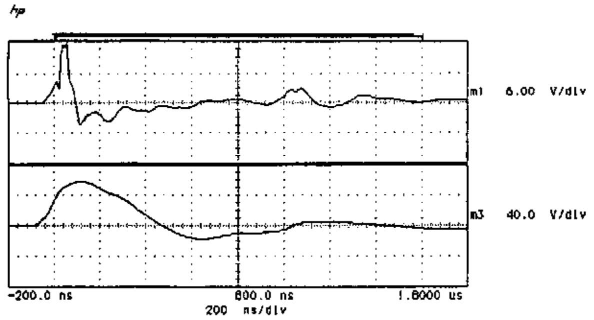
Figure 6 - Scheme of injection with test generator

The applied waves are:

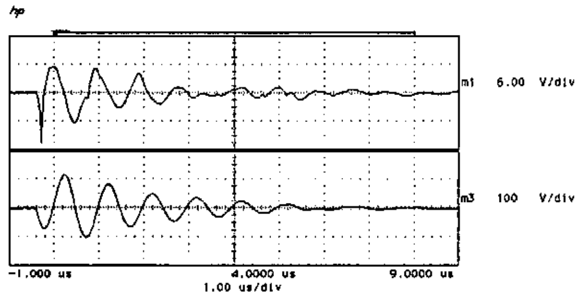
- *damped oscillatory wave* with frequency of 1 MHz and amplitude of 2.5 kV, produced by type NSG 505 Schaffner generator, accordingly to the relevant standard [4];
- *electrical fast transients/burst* 5/50 ns wave with amplitude of 4 kV, produced by PB 4a Haefeely generator through FP 16/3-1 coupling network of 50 dynamic impedance also accordingly to the relevant standard [5].

The waves of the common mode voltages (related to the screen) have been, subsequently recorded in the same way as described above. A record is plotted - as an example - in Fig. 7.

The shielding effectiveness of the traditional and new screens can easily be verified on the bases of



a) Damped oscillatory wave



b) Fast transient/burst

Upper wave: New filled 30x1.5
Lower wave: Traditional 30x1.5
Fig. 7 - Common mode voltages due to injection by test generators

the ratios plotted for the maximum amplitudes of the damped oscillatory and transient/burst waves in Tab.8.

Table 8 - Common mode voltage rations new screen compared with traditional

Screen type		Transient type	Ratio
new filled (upper wave)	*traditional* (lower wave)		$\frac{\text{new}}{\text{trad}}$
30x1.5	30x1.5	*Damping*	0,06
		Burst	0,18
4x2.5	4x1.5	*Damping*	0,06
		Burst	0,18
14x1.5	30x1.5	*Damping*	0.05
		Burst	0.13

The ratios verify a higher improvement in the shielding effectiveness seems for the damping oscillatory wave than that of for the fast transient/burst wave, having higher frequency composition. The reason for this conflicting result may also be the increase in the internal surface (transfer) impedance due to the additional inductance caused by the spiralling effect, as it has already been mentioned in connection with Tab. 1.

V. CONCLUSIONS

Regarding the requirements on and the performance of the signalling cable with new design the following conclusions can be made.

1) 50 Hz performance:

- Reliable current carrying capacity required:
  - 10 to 100 A for continuous screen current;
  - order of 1000 A under fault condition.
- Screening factor is controllable by:
  - filling rate of the wire screen (independently from the diameter of the screen);
  - thickness of the steel tape armour (0.3 mm is suitable in the most cases).

2) High frequency performance:

- Only ratios could be identified (considerable screening with open screen);
- One order of magnitude improvement has been reached due to new design;
- Lower (better) ratios are identified for damping wave than for burst (1/3);
- Ratios for HF transients due to HV switching are between the ratios for damping wave and burst
- The traditional screen has also significant screening for HF.

ACKNOWLEDGMENT

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