Aspects Related to Replacing HV Lines by HV Cables on Resonant Grid Behavior

L. Wu, P.A.A.F. Wouters, E.F. Steennis

Abstract--**At different places worldwide EHV/HV connections partly consist of sections with underground power cables. Presently in the west of the Netherlands 20 km (i.e. 240 km single phase in total) of power cables is planned in a new 380 kV connection (Randstad380 project) grid to ensure sufficient transport capacity in the Randstad area for the next decades. One of the issues studied in this project is the uncertainty about possible over-voltages from resonances. The paper intends to give a discussion on types of over-voltages, transients and possible resulting resonances reported in literature for combined line-cable circuits. These over-voltages include: switching over-voltage, temporary over-voltage and system-interaction over-voltage. System simulation results will be presented as well.**

Keywords: **Resonance, power transmission, power cables, power system harmonics**

I. Introduction

VARIOUS reasons, e.g. related to environmental, political, operational or geometrical aspects, drive the utilization of power cables instead of power overhead lines. However, the electrical characteristics of cables and overhead lines are different, so the feasibility of the choice of power cables needs to be investigated regarding to the effect brought by cables on grid behavior.

The capacitance of the cable connection will be compensated by shunt reactors for power factor correction. These elements together with parasitic elements of connected electrical components such as the parasitic line capacitances or transformer winding inductances can give rise to transient over-voltages. With a large scale power system, resonances may occur in the line/cable itself or in connected grids. This paper mainly focuses on the resonance aspect. Various hypothetical cases are analyzed to exemplify possible causes of resonant behavior.

In Section II, the basic principles of resonance are discussed. In Section III, the common types of over-voltages related to resonance are systematically discussed, and reported resonances in literature are incorporated. In Section IV, system simulations of basic examples of possible over-voltages for circuits containing a cable connection are presented, and the results are analyzed. In Section V conclusions are given.

II. Definition and Principles of Resonance

One definition of resonance in an electrical system is that a vibration of large amplitude in an electrical system is caused by a relatively small periodic stimulus of the same or nearly the same period as the natural vibration period of the system [1]. Here, the vibration means the energy is transferring back and forth between two parts (inductor and capacitor). In this definition, one of the premises is that the stimulus is periodic. Indeed, some operation will have the phenomena that the energy is transferred with a frequency close to the natural frequency defined by the involved inductance and capacitance. In other situations, there is no periodic stimulus. Resonant behavior occurs by an excitation, e.g. switching. Hence, the resonances both with and without periodic stimulus are included in this paper.

A. With Periodic Stimulus

Generally there are two types of resonance related to the connection of inductor and capacitor; parallel resonance and series resonance. Reference [2] gives a detailed discussion on these types of resonances, see Fig. 1.

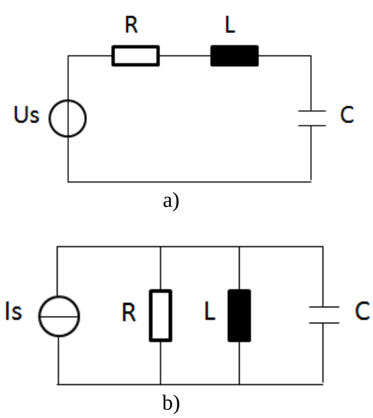

Fig. 1. Resonance Circuit Diagram; a) Series resonance, b) Parallel resonance

The natural frequency of the circuits in Fig. 1 is

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad (1)$$

When the frequency ω of the periodic stimulus, U_S in Fig. 1a

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or I_S in Fig. 1b meets

$$\omega = \omega_0 \qquad (2)$$

resonance occurs. These resonances require periodic stimulus, which may come from harmonic sources or induced by a system nearby via system interaction, in practice. Both parallel and series resonances are discussed from a power system point of view in [3].

B. Without Periodic Stimulus

The switching event is another cause for resonance as illustrated in Fig. 2. Here, U_S stands for the busbar, Z is the equivalent source impedance, CB is the circuit breaker, L is the shunt reactor for power factor compensation, and C is the equivalent capacitance of an unloaded transmission overhead line or cable. In this situation, if CB opens, the energy stored in L and C before switching will transfer back and forth between L and C, until being damped out by the equivalent resistance within the loop of L and C. The frequency equals the natural frequency ω_0, given by (1).

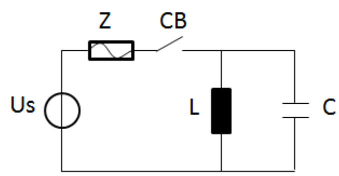


Fig. 2. Resonance example according to switching event in power system

III. COMMON TYPES OF OVER-VOLTAGES

Over-voltage is one of the most important issues to investigate for EHV/HV power systems. According to IEC 60071-1/1 they can be classified based on their waveform [4]. For this paper a classification in terms of their cause, see e.g. [5], is taken:

1. Switching over-voltages
2. Temporary over-voltages
3. System interaction over-voltages
4. Lightning over-voltages

The lightning over-voltage corresponds to very a fast transient and the duration is very short; it is beyond the scope of this paper. In the following subsections, the basic principles of over-voltages related to resonant behavior among the other three types are discussed. Resonance over-voltages are classified as switching over-voltages if they originate from (dis-)connection operations, as temporary over-voltages [6] if their duration is relatively long, e.g. several seconds [5], and as system interaction over-voltages if they are induced by a nearby system.

A. Resonance due to Switching Operation

In EHV/HV power systems, the switching over-voltage is the dominant concern for system operation [7], for its ability of damaging power devices and harming personnel. Fig. 2 shows a simplified equivalent circuit diagram for illustration of switching a cable with a single shunt reactor. Usually, a cable has shunt reactors on both sides. The disconnection of capacitor C can essentially stand for switching off an unloaded overhead line or cable, as is pointed out in [7]. Normally, the major part of the system impedance Z is inductive, and its value is small compared to the impedance of the shunt reactor L and cable capacitance C, otherwise the regulation is too weak [7]. Therefore, before the CB opens, the voltage over C is

$$U_C(0) \approx U_S \qquad (3)$$

Actually, the voltage of the cable can be higher than the source voltage depending on compensation rate, i.e. the ratio of the total reactive power of shunt reactor and the reactive power of the cable [6]. If the compensation rate is lower the voltage on cable is higher. However, reference [6] shows, that a completer compensation rate is not necessarily better regarding to zero-cross missing. When the CB is opened, the circuit will be interrupted as the current reaches its natural zero crossing point. Meanwhile, the source voltage U_S reaches its peak. This means, the initial value of the current of L is

$$I_L(0) = 0 \qquad (4)$$

An electrical oscillation occurs between L and C, according to

$$\begin{cases} U_C = L\dfrac{dI_L}{dt} \\ I_L = C\dfrac{dU_C}{dt} \end{cases} \qquad (5)$$

$$U_C = U_S \cos(\omega_0 t) \qquad (6)$$

Although the value of U_C will never be larger than U_S, this is a dangerous situation since the shunt reactor and cable, which are intended to be switched off, still are at high potential. Besides, the voltage across the CB is determined by the voltage difference between its two sides, the source voltage U_S, which is varying with power frequency, and the capacitor voltage U_C, which varies with the natural frequency ω_0. Reference [8] points out that in practice, the reclosing of a circuit breaker a few power frequency cycles later than its previous interruption is quite common due to improvement in system stability. In special circumstances, the shunt reactors are switched off before the unloaded cable is switched off. Together with the fact that the circuit breaker will interrupt the circuit probably at the first current zero crossing point, if the amplitude of the current in switching an unloaded cable is small, the voltage across the CB will reach $2{\cdot}U_s$ rapidly, while the separation of the CB contacts is still small. If the voltage is higher than the CB withstand voltage, the CB will re-ignite via an arc. According to e.g. [7] reclosing due to operation commands or re-ignition due to arc re-establishing U_C can reach values of several times higher than U_S. This can exceed the insulation coordination requirement and cause damage to power devices. Reference [8] gives a discussion on the reclosing of a line with compensated rate of 80% by shunt reactors. The voltage across the contacts of a circuit breaker can reach as high as four times the nominal voltage of the system. Further studies on resonances upon switching include [6],[9]. Especially [9] provides extensive investigations on the switching over-voltages with permanently connected shunt reactors, in combined 400 kV cable and overhead line system.

B. Ferroresonance

Ferroresonance can occur during a switching operation where iron cores are involved. It is discussed as separate subsection because of its special importance in system operation. Ferroresonance is mostly caused by transformer switching operation, and is related to the nonlinear saturable characteristics of the iron. Reference [10] classifies reported ferroresonant circuits based on reviewing 129 papers: “

1. Transformer supplied accidentally on one or two phases.
2. Transformer energized through grading capacitance of circuit breaker.
3. Transformer connected to a series compensated transmission line.
4. Voltage transformer connected to an isolated neutral system.
5. Capacitor voltage transformer
6. Transformer connected to a de-energized transmission line running in parallel with one or more energized lines.
7. Transformer supplied through a long transmission line or cable with low short-circuit power.”

The resistive element in Fig. 1a is ignored as simplification, so that a circuit for series resonance between the transformer inductance and the cable capacitance is established. Due to the nonlinearity of the iron core of the transformer, the inductance is a function of current *I*, and the voltage over *L* depends on the source frequency ω and a function of *I*.

$$U_L = \omega \cdot f(I) \qquad (7)$$

The voltage over *C* is

$$U_C = -\frac{I}{\omega C} \qquad (8)$$

The negative sign indicates that U_L and U_C have opposite directions in phasor-diagram. According to the circuit

$$U_L = U_S + \frac{I}{\omega C} \qquad (9)$$

With ferroresonance, the voltages of both U_L and U_C can be higher than the source voltage U_S, and may even exceed the withstand limits of power devices. References [7],[11] provide a detailed discussion. Fig. 3 is an example of resulting U-I curves in a ferroresonant circuit. The nonlinear bold line is sketched according to (7), whereas the straight lines represent (8), drawn for two different *C* values. The intersections define the operation points: *p*, *q*, *s* and *t*. Point *p* is an unstable operation point meaning that it will not persist in steady state, but could show up in a transient. Points *q* and *t* are stable. If the system moves to point *t*, the voltage and current both will be high. If the *C* is relatively small, the corresponding intersection *s* may even be the only operation point.

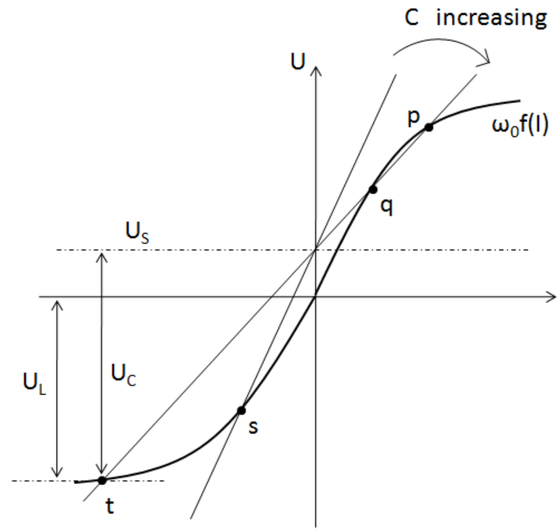


Fig. 3. Ferroresonance basic principle

Although normally the surge arrester will trip to reduce the over-voltages, repeated tripping due to sustained resonance will also cause damage to the surge arrester. Reference [12] discusses an example of energizing an unloaded transformer in high-voltage system with a real typical B-H curve of transformers resulting in resonance voltages exceeding the equipment withstand capability.

C. Resonance due to harmonics

Harmonics is a third important source of resonance over-voltages. Harmonics can be generated by any nonlinear component in the power system, e.g. transformer core, power electronics and so on. Harmonics can also be induced by a nearby system, which is called system interaction. The harmonics are often indicated by equivalent current sources [3]. In Fig. 1b for example, the current source I_S, which stands for the harmonic source in the system due to a nonlinear component or induced by a nearby system, is a periodic stimulus. *L* and *C* are parameters of power components in the power system. If the harmonic frequency is equal to or near the natural frequency of *L* and *C*, the resonance between them will generate over-voltages, and it will persist still after the source I_S is switched off until the stored energy is dissipated. Reference [3] gives a detailed discussion on harmonic resonances.

IV. System Simulation and Results Analysis

In order to provide examples for analyzing the resonance in high-voltage system including a power cable, simulations with MATLAB Simulink are discussed in this section. For demonstration purpose, a single-phase model is chosen [8]. The cables are modeled as distributed parameter transmission lines using the Bergeron model [13]. The calculated over-voltages are presented in Per Unit (p.u.):

$$\frac{\sqrt{2}}{\sqrt{3}} 420\,kV \approx 343\,kV \qquad (10)$$

A. Cable Switching

The simulation model for cable switching is shown in Fig. 4; U_s is the 380 kV network source with amplitude equal to 380/420=0.9 p.u., L_s is the source impedance and C_s is the equivalent parasitic capacitance on the source side of the circuit breaker CB. L_1 and L_2 are the shunt reactors. The close state of the circuit breaker is modeled as a resistor of 0.01 Ω. The cable parameters are taken similar to [6], see Table I, and the cable length is 20 km.

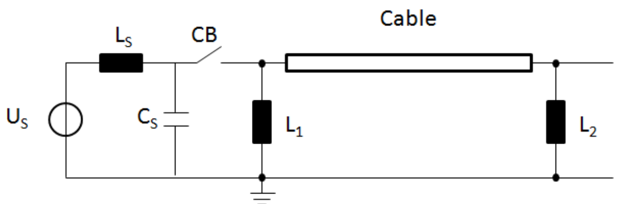


Fig. 4. Resonance between cable and shunt reactors when cable is switched off

TABLE I
CABLE PARAMETERS FOR EXAMPLE IVA

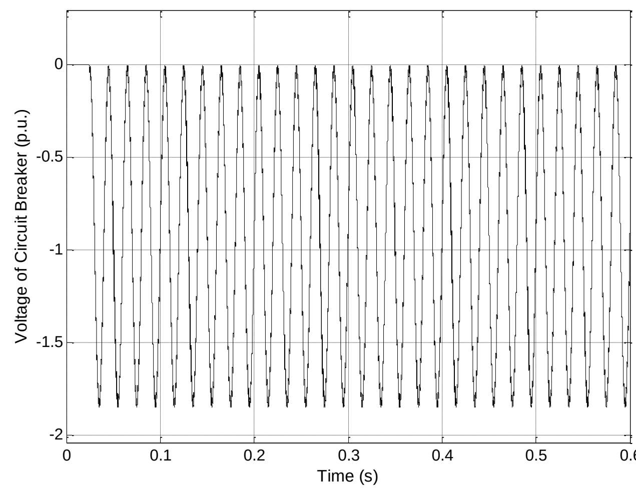
Cable Parameters	Values
R_c	10.5 mΩ/km
X_c	223 mΩ/km
C_c	0.24 μF/km

Figures 5 a-c) shows the circuit breaker voltage after the cable is switched off with different compensation rates. The cable is switched off at time t=25 ms in the simulation.

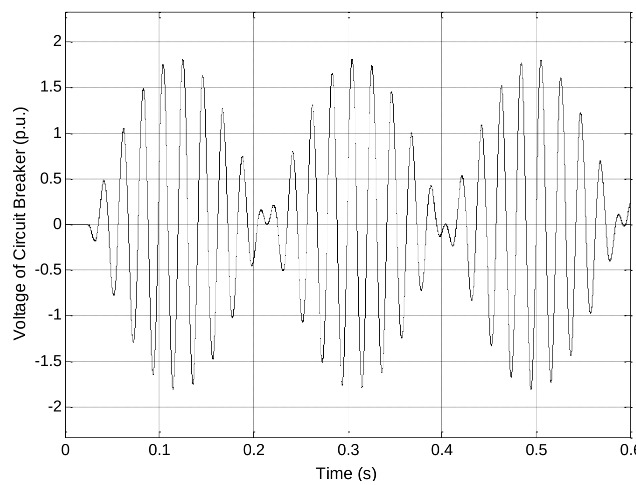
Figure 5a is the situation without compensation. The shunt reactors are disconnected before the cable is switched off. The peaks of the curve slightly shift from zero, because the voltage of the cable is higher than the source voltage when the circuit breaker opens due to the capacitive load. The right side of the circuit breaker has a steady voltage which is a little higher than the amplitude of the source voltage, while the left side of the circuit breaker is varying with the source voltage. Its value nearly equals the source voltage because the reactance of L_s is much less than that of C_s. Hence, the voltage of the circuit breaker is always negative, and its value varies between about -1.8 p.u. and 0.

In Fig. 5b and 5c, the shunt reactors are connected to the cable with 80% and 90% compensation, causing a resonance with the cable capacitance. The peak value of each cycle is modulated because the frequencies of the voltages on both sides of the circuit breaker are different. By comparing Fig. 5a, 5b and 5c it can be seen that the compensation increases the time for the voltage over circuit breaker to reach an amplitude of about 1.8 p.u.: in a), it is the first peak after the circuit breaker interrupts the circuit; in b), it is in the fifth cycle; in c), it is in the ninth cycle. Hence, the situation with 0% compensation rate is most likely to cause re-ignition in the circuit breaker which can cause over-voltage. The reclosing of circuit breaker in a), b) or c) may also cause over-voltage.

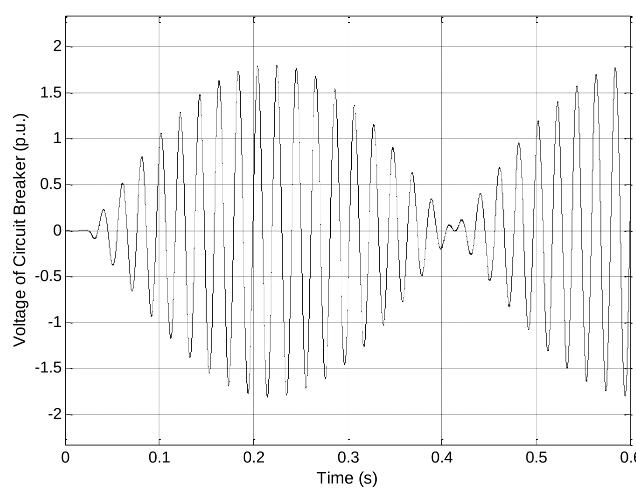
Figure 5d gives the resulting voltage at the cable remote end by the reclosing of the circuit breaker, as an example. The cable is 80% compensated. According to b), the first highest peak is at about 0.115 s if the circuit breaker is pre-opened at 0.025 s. Hence, the circuit breaker is set to be reclosed at 0.115 s.



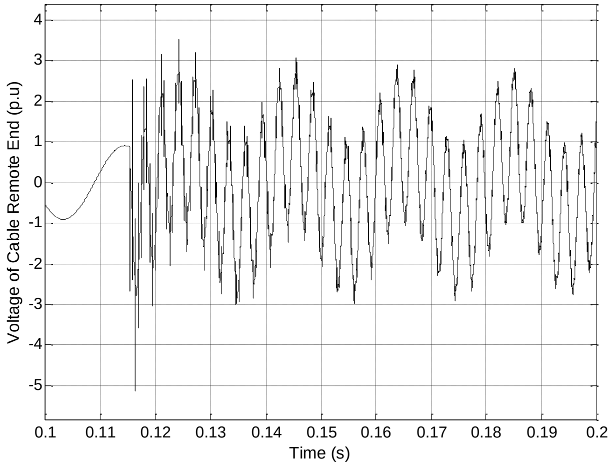
a)



b)



c)



d)

Fig. 5. Voltage of circuit breaker during cable switching. a) 0% ; b) 80% compensated; c) 90% compensated; d) Voltage of cable remote end after reclosing with cable 80% compensated.

The narrow spikes are caused by the reflection and superposition of traveling waves which travels back and forth along the cable. The time interval between consecutive spikes corresponds to the travel time over the distance of two times the cable length. The transient amplitudes decrease due to losses during propagation. The peak voltage value of the cable remote end without spikes can reach over 2.5 p.u.; including spikes it can reach almost 5.0 p.u..

B. Transformer Switching

The simulation model for transformer switching is shown in Fig. 6. The values of U_s, L_s, C_s and the cable are the same as those in Fig. 4. The compensation rate of the cable is 80%.

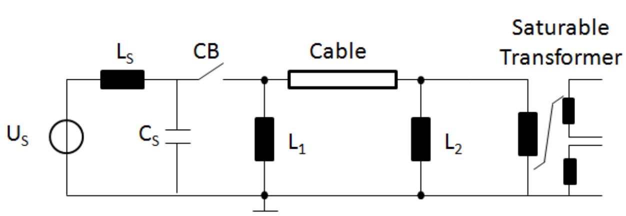


Fig. 6. Resonance between transformer and cable when transformer is being connected.

The ratings of the transformer are 50 Hz, 400/275/13 kV and apparent power is 750 MVA. The nonlinearity of the transformer refers to the primary side is taken from [6], see Table II. The resulting voltage curve of its primary winding is shown in Fig. 7.

The circuit breaker closes at time point of 5 ms. It can be seen from Fig. 7 that there are also transient voltages caused by traveling waves, similar to Fig. 5d, and the highest voltage peak without spikes is around 1.8 p.u.. Including spikes, the highest voltage value then exceeds 2.0 p.u..

TABLE II
NONLINEARITY OF THE TRANSFORMER

Current (A)	Flux (Wb)
0.04	917.29
0.10	978.44
0.18	1039.6
0.41	1100.75
1.15	1161.9
3.51	1223.05
7.97	1284.21
117.60	1467.66

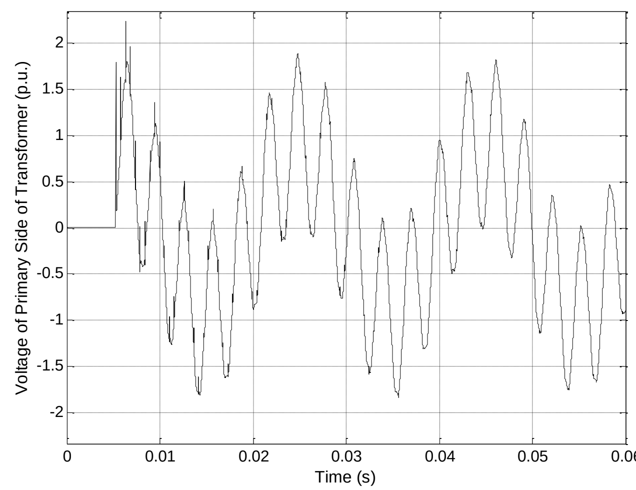


Fig. 7. Resonance between cable and transformer, together with shunt reactors.

C. Harmonic Resonance

The simulation model for harmonic resonance is shown in Fig. 8. The length of the cable is 20 km with a compensation rate of 80%. There is an inductive load of about 1194 MVar connected to the end of the cable. The rated current of the load is about 1814 A, which is acceptable due to the rated current of the cable is in the range of 1400-2500 A. The harmonic source is an equivalent current source I_s, connected at the other end of the cable, exciting the 7th harmonic of the fundamental frequency of 50 Hz. The magnitude value of the harmonic current source is taken 10 A, which is about 0.4% of the rated load current. This source could represent a nonlinear device or be induced by a nearby system via system interaction.

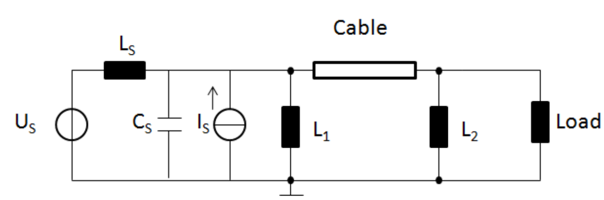


Fig. 8. Resonance caused by harmonic sources

The resulting voltage of the resonance is shown in Fig. 9. There is a significant over-voltage whose peak even approaches 5.0 p.u.. This is a special case only meant as an example. The resonance occurs because the natural frequency of the system happened to be very close to the 7th harmonic power frequency.

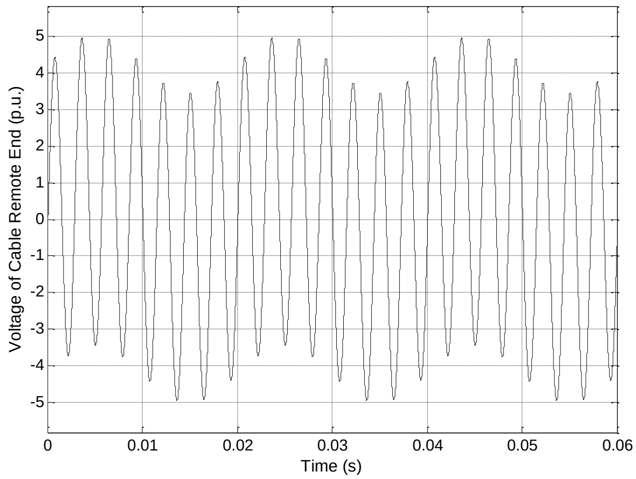


Fig. 9. Voltage of cable remote end caused by harmonic source

V. CONCLUSIONS

Resonances without and with periodic stimulus are investigated by disconnection, transformer energizing and harmonic sources respectively in basic circuits containing a power cable.

The voltage across the circuit breaker when switching off an unloaded cable can reach about 1.8 p.u., and this value is reached faster if the compensation rate is lower. The re-ignition and reclosing of the circuit breaker can cause several times higher voltage than the nominal system voltage on the cable.

The energizing of an unloaded transformer with cable will also cause resonance between transformer and cable, and its peak can be higher than 2.0 p.u..

The harmonic source can also cause resonance over-voltage which can reach about 5.0 p.u., when the frequency of the harmonic source equals the natural frequency of the network.

The simplified conditions already indicate that careful considerations should be given to partly cabling of high-voltage lines. For more realistic analysis of a real (three-phase) grid on resonant behavior it is however not sufficient to extract small sub grids, since resonance can be caused by complex system interactions.

VI. REFERENCES

[1] Merriam-Webster Online Dictionary. Available: http://www.merriam-webster.com/dictionary/resonance

[2] C. K. Alexander, and M. N. O. Sadiku, *Fundamentals of Electric Circuits.* 2nd Edition, McGraw-Hill Inc., 2002, p. 630.

[3] J. Arrillaga, and N. R. Watson, *Power System Harmonics.* 2nd Edition, John Wiley & Sons Ltd., 2007, p. 143.

[4] *Insulation co-ordination - Part 1: Definitions, principles and rules*, IEC-60071-1/1 standard, 2006.

[5] Leonardo Energy, "Power Quality and Utilisation Guide: Voltage disturbances: Transient and temporary over-voltages and currents," June 2007. http://www.leonardo-energy.org/webfm_send/198

[6] Tokyo Electric Power Company, "Assessment of the technical issues relating to significant amounts of EHV underground cable in the all-island electricity transmission system: Public Report," Nov. 2009.

[7] A. Greenwood, *Electrical Transients in Power Systems.* 2nd Edition, John Wiley & Sons, Inc., 1991, p. 92.

[8] R. D. Garzon, *High Voltage Circuit Breakers*. 2nd Edition, Taylor & Francis, 2002, p. 98.

[9] C. L. Bak, and K. Søgaard, "Recent advances in electric power systems, high voltages, electrical machines," *Proceedings of the 8th WSEAS International Conference on Electric Power Systems, High Voltages, Electric Machines (POWER '08):* WSEAS Press, 2008, p. 99-108.

[10] D. A. N. Jacobson, "Examples of ferroresonance in a high voltage power system," Power Engineering Society General Meeting, IEEE, 2003.

[11] S. Santoso, R. C. Dugan, T. E. Grebe, and P. Nedwick, "Modeling Ferroresonance Phenomena in an Underground Distribution System," IEEE IPST '01 Rio de Janeiro, Brazil, Jun. 2001, paper 34.

[12] C. P. Cheng, and S. Chen, "Simulation of resonance over-voltage during energization of high voltage power network," IPST, in New Orleans, USA, 2003.

[13] N. Watson and J. Arrillaga, *Power Systems Electromagnetic Transients Simulation*. The Institution of Electrical Engineers, London, United Kingdom, IEE Power and Energy Series 39, 2003.