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# DALI LIGHTING CONTROL INTERFACE CIRCUIT AND ELECTRICAL CHARACTERISTICS OF A TYPICAL DALI CABLE

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**ABSTRACT**

This study focuses on DALI lighting control interface and DALI cabling. DALI interface circuit will be designed and presented. DALI wiring is typically made by using a standard PVC (polyvinyl chloride) insulated electrical cable. Electrical characteristics of such a cable will be defined to fully understand the frequency dependent behaviour of the cable. The self-inductance, mutual inductance and resistance of the cable will be resolved by using a numerical method called volume fillet. PVC material data, like the relative permeability and the loss tangent, will be resolved by using the results of material science studies. A lumped model presentation for the cable will be created. Time dependent simulations for the interface and the cable will be executed using Spice. The usability of the lumped model will be issued. The lumped model can be extended to a distributed model. Neither of these models can handle the frequency dependence on the electrical characteristics. There are some options how to improve the model.

**Keywords:** DALI, digital lighting control, volume fillet method.

## INTRODUCTION

DALI (Digital Addressable Lighting Interface) is a digital light control bus which uses two wires or twisted wire pair. DALI has been introduced and developed by DALI development group which includes a large number of companies in lighting business. DALI has been in use since early 1990s and it has become the most well known digital light control bus. DALI was first mentioned in standard IEC60929 [1] in the year 2003. The standard was about dimming fluorescent lamp ballasts. The standard didn't say anything about LED lamps. Standard IEC60386 become in the year 2009 and it presented DALI as the lighting control for LED lamps. DALI is becoming more widely used in LED lighting control. Compared with any other control buses used before, DALI is digital, primary intended for lighting purposes and features bidirectional communication. Bidirectional means a controller can send a request to ballast and the ballast(s) can answer for that. There can be more than one controller in the bus. In addition to lighting ballasts there can be also some other devices and accessories used in lighting or building automation. These devices, as mentioned in the standard, can be for example: switches, scene controllers, dimmers, proximity or occupancy sensors, daylight controllers and communications modules. DALI standard defines a connected device to be either a slave or a master. Controllers are masters as they can command or start communication. The rest are slaves. In terminology of DALI, slaves are often called electronic control gears (ECG). Communication modules are converters between DALI and other control systems like DMX512 (lighting) and KNX (home/building automation). DALI has been copied and reprinted also by NEMA [2-3].

From the hardware point of view DALI is rather simple. Two wires features half-duplex communication. Compared with the other light control standards, the benefit of DALI is the bidirectional operation. Data can be requested from the light ballast or from the other devices connected in the bus. Communication takes place using a rather slow speed, 1200 bits/s and using rather high voltage levels. High voltage levels mean high immunity to noise from other electrical wires or devices. Voltage of the bus is nominally 16 V, but it can vary between 11.5 V and 22.5 V. Logic levels are: logic zero -6.5 - 6.5 V and logic one 9.5 - 22.5V. According to the standard, devices connected to the bus are either ballasts (slaves) or controllers (masters). The maximum number of devices in the bus is 64 ballasts and 64 controllers. DALI standard does not request certain kind of cable to be used. Typically, DALI is wired using the same kind of electrical cable as is used for electrical installations in a building. The maximum length depends on the conductor cross section. The standard sets the maximum allowed voltage difference between two devices, and that voltage is 2 V. The maximum current in the wire is specified to 250 mA. These values with the resistivity of the conductor set the maximum cable length.

At the initial state DALI line is high which also indicates logic 1. Logic zero is done by pulling down the line. At that moment, power is consumed. There must be a power supply unit connected to the bus. Like the cable type, the wiring topology can be chosen quite freely. Various topologies are possible like a star or a mesh, but a ring is not recommended. Data is transmitted differentially, which means the wires are equal in DALI. There is no risk to connect the device wrongly. DALI includes both hardware and software protocol. It is indeed a wired control bus. While the use of DALI has expanded and integrated into home automation [4-5], DALI protocol has been adopted also to many wireless solutions [5]. Strictly speaking DALI is only a wired control bus defining both the hardware and the software protocol.

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DALI waveform and the timing specification is presented in Figure-2 [3]. DALI basics are presented in many papers [4, 6-8].

Software brings the complexity to DALI. Communication means sending frames in two directions. Controlling light ballast can simply be unidirectional communication where the controller sends commands to the slave. This communication uses 2 byte commands. The possible response may be only one byte. Communication between controller type devices uses 3 byte commands. DALI includes a large number of general commands and a method of expanding the commands in order to access even a larger command set. There are also broadcast commands for all devices or for all devices of selected type or for a selected group of devices. At symbol level DALI uses Manchester coding. DALI uses CSMA/CD principle and five (0-4) priority levels.

This study focuses on the hardware of DALI. Each DALI device has an interface circuit which features an opto-coupled connection to the bus. The main idea of DALI is a simple and an inexpensive solution to lighting control. Therefore the interface circuit is normally made by using the smallest component count and selection of inexpensive components. The design challenge is to ensure the interface is capable of driving the load of the maximum length cable.

The other issue in this study is the cable type used in bus wiring. The wiring is normally done by using a standard PVC insulated 500/300 VAC, 50/60Hz rated electrical twin core cable which for communication application is far from the ideal. It is important to find out what limitations such a cable may have. This study proceeds first by modelling the cable using the volume fillet method and then creating a lumped model for the cable. The model can then be included in Spice simulations. The next step could be the use of a more accurate model for the cable which includes frequency dependence on the model components.

## DALI INTERFACE AND DALI POWER SUPPLY CIRCUIT

Figure-1 shows the complete DALI interface and DALI power supply. Only the power supply end stage which is based on a linear regulator circuit is included in this simulation model. The regulator is composed of transistor Q6, resistors R16-17 and diodes D9-D10. DALI transmitter side is made of optocoupler X1, transistors Q1-2, mosfet M1 and the resistors around them. The receiver side is composed of transistors Q3-4, optocoupler X2 and resistors around them. Another regulator circuitry is made of transistor Q5 and the components around it. Input to this regulator comes from DALI lines (D+, D-) and it provides supply voltage for the components which are on DALI line side. The mosfet should have a low $R_{DS(on)}$ in order to feature low logic 0 level. Optocouplers are often slow components and in this circuit the optocoupler X1 causes the low rise time of DALI waveform.

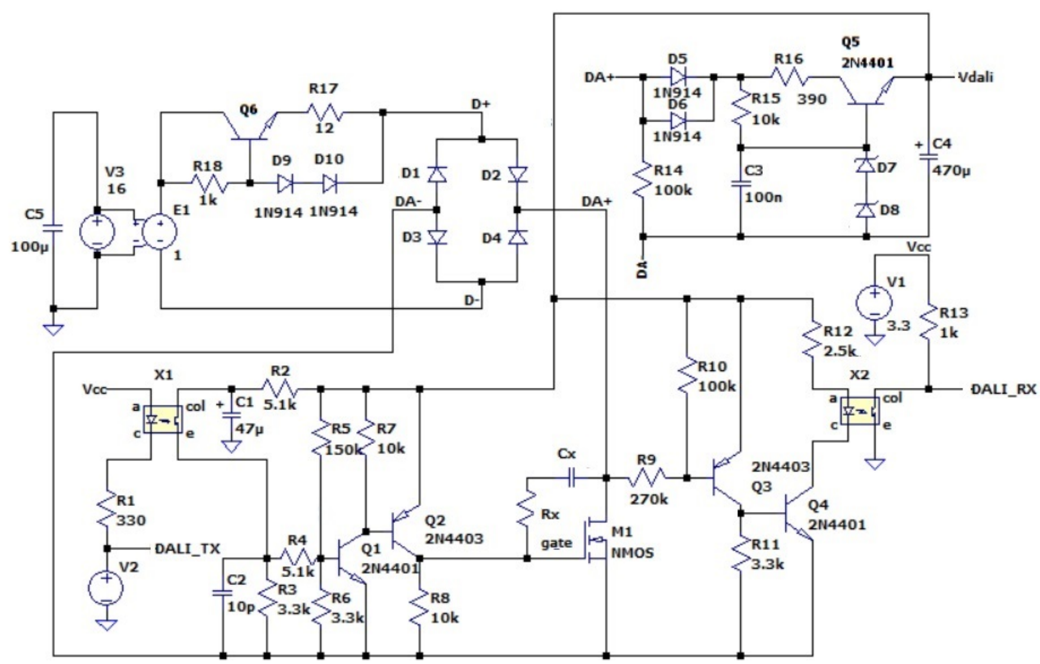


**Figure-1.** The simulation circuit includes DALI interface and DALI power.

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**DALI CABLE**

DALI standard does not require certain specific type of a cable to be used for wiring. The standard specifies only the maximum voltage drop between two devices. The cable provides power for DALI devices connected to the bus. DALI bus wiring is often done with 1.5 $mm^2$ copper pair of wire. That is the same kind of wire used for electric wiring in a building. This wire is intended for 50/60 Hz and up to 500V voltages and therefore its high frequency characteristics are rather poor. Insulating material is PVC which results in high capacitance value. It is difficult to find AC electrical specifications extending the normal power line frequency. Electrical characteristics must be measured, simulated (FEM) or resolved by calculations. DALI uses rather low 1200 bit/s speed with signal rise/fall times between 10-100 us. This mean the fundamental frequency component is around 1.2 kHz and the essential spectral content is well below 10 kHz.

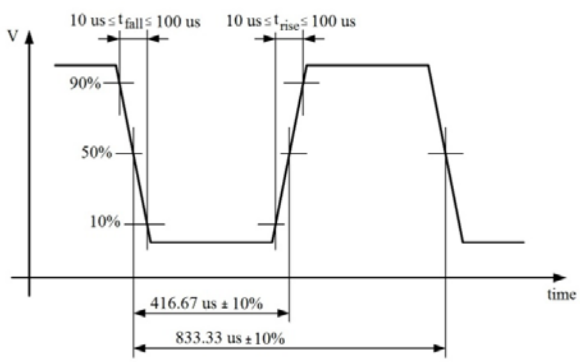


**Figure-2.** DALI waveform. The timing specification.

The electrical characteristics of DALI cable are found by using a numerical method called volume fillet. The method results frequency dependent parameters R(ω), $L_s(\omega)$, $L_m(\omega)$ of the cable. A lumped model for the cable can then be created. A better model would be a distributed model which is composed of a large number of lumped models. This model match better to reality as the electrical parameters are distributed along the cable length. However both of them model the cable at specific frequency and underestimate the high frequency losses of the cable.

**A. Self-inductance of a wire and mutual inductance of a wire pair**

Equations for a self-inductance $L_s$ of an isolated single wire and a mutual inductance $L_M$ of a wire pair can be found [9]. These equations are used in the numerical solution for the frequency dependent inductances of a wire pair. In the equations (1-2) dimensions are entered in meters and inductance will be in microhenries (μH).

$$L_s[\mu H] = 0.2\left\{ l \ln\left(\frac{l+\sqrt{(l^2+r^2)}}{r}\right) - \sqrt{(l^2+r^2)} + \frac{l}{4} + r \right\}$$

$$\approx 0.2\, l \left\{ \ln\left(\frac{2l}{r}\right) - \frac{3}{4} \right\} \qquad (1)$$

The wire radius is r and length *l*. The approximation is valid if $l >> r$.

$$L_M[\mu H] = 0.2\left\{ l \ln\left(\frac{l+\sqrt{l^2+d^2}}{d}\right) - \sqrt{l^2+d^2} + d \right\}$$

$$\approx 0.2\, l \left\{ \ln\left(\frac{0.2\, l}{d}\right) - 1 + \frac{d}{l} \right\} \qquad (2)$$

The distance between the centres of wires is d. The approximation is valid if $l >> d$.

The capacitance of the wire pair can be calculated by using equation (3), where s is the distance of the wires.

$$C = \frac{2\pi\epsilon l}{\ln(s^2/r^2)} \qquad (3)$$

The equation results are values of inductance for the dc and the low frequency conditions. At higher frequencies, the skin effect has an effect on the effective cross section of the wire. Current will be concentrated inside the layer which has depth δ from the conductor surface.

$$\delta = \frac{1}{\sqrt{(\pi \mu \sigma f)}} \qquad (4)$$

Where μ is the magnetic permeability, σ the electrical conductivity of the wire and f is the frequency.

$$R_{dc} = \frac{l}{\sigma A} \qquad (5)$$

$$R_{ac} = R_{dc} + R(f_c)\sqrt{(f/f_c)} \qquad (6)$$

Equations (1-6) are adequate to model the frequency dependency of wire inductance. These equations are used in the volume fillet method described next.

**B. Calculating electrical characteristics of a cable**

In the volume fillet method, the conductor is divided to a number of subconductors in such a way that the cross section of the conductor equals the sum of the cross sections of the subconductors. The method calculates frequency depended current of each subconductor. The subconductors are electrically parallel and the total current

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is equivalent to the current of the original conductor. The currents can be calculated from a large number of equations and therefore it is better to write and solve those equations in matrix form. In order to get accurate results, the number of subconductors should be large. The current is considered to be evenly distributed across each cross section of the subconductor. At higher frequencies, the skin effect becomes more and more significant. As the skin effect forces the current to flow closer the surface the number of subconductors included in calculations reduces.

The solution of the matrix equation for the single isolated wire results in frequency dependent values for the resistance and the self-inductance. Matrix equation for a pair of wires can be constructed similarly than in the case of a single wire. The solution of the matrix equation results in frequency dependent values for the resistance and the mutual inductance of the wires.

Use of the volume fillet method is not limited to a certain shape of conductors. The rectangular shape of a conductor is the most obvious shape when considering an integrated circuit or a circuitry on a printed circuit board. Wires in cables usually have a circular shape. A wire of a circular cross section can be constructed using subconductors with a rectangular cross section as shown in Figure-3.

The matrix equation which includes the resistance, the self-inductance and the mutual inductances between the subconductors of the same wire is represented below.

$$V(s)\begin{bmatrix}1\\1\\\vdots\\1\end{bmatrix}=r\begin{bmatrix}i_1\\i_2\\\vdots\\i_N\end{bmatrix}+s\begin{bmatrix}L_s & M_{12} & \cdots & M_{1N}\\M_{21} & L_s & \cdots & M_{2N}\\\vdots & \vdots & \cdots & \vdots\\M_{N1} & M_{N2} & \cdots & L_s\end{bmatrix}\begin{bmatrix}i_1\\i_2\\\vdots\\i_N\end{bmatrix} \qquad (7)$$

As the inductance matrix has the size of N x N the r $[i_1, i_2, ...i_N]^T$ must be multiplied with an identity matrix $\mathbf{E}_N$. Matrix r $E_N$ $I_N$, where $I_N$ is a unity vector, become N x N matrix.

$$V(s)1_N=(r\boldsymbol{E}_N+s\boldsymbol{L})\boldsymbol{I} \qquad (8)$$

where $1_N$ is a unity vector size Nx1 and the current vector I has the size of Nx1. From this equation, the total admittance $Y_t$ is solved by matrix inversion.

$$Y_t=\mathbf{1}_N^T(r\boldsymbol{E}_N+s\boldsymbol{L})^{-1}\mathbf{1}_N \qquad (9)$$

The result $Y_t$ can be divided two parts Re $\{Y_T\}$ = 1/R and i·Im$\{Y_t\}$ = 1/sL$_s$.

Similar matrix equation can be written for the case of wire pair. In that case, the mutual inductances are between the subconductors of separate wires. The inductance matrix becomes larger than for the case of a single wire.

If wire 1 has been divided for N1 and wire 2 for N2 subconductors, the inductance matrix has size of (N1+N2) x (N1+N2).

$$[V_1(s), V_2(s)][\mathbf{1}_{N1}, \mathbf{1}_{N2}]^T = \begin{bmatrix} r_a\boldsymbol{E}_{N1}+s\boldsymbol{L}_a & s\boldsymbol{M}_{ab}\\ s\boldsymbol{M}_{ab}^T & r_b\boldsymbol{E}_{N2}+s\boldsymbol{L}_b\end{bmatrix}\begin{bmatrix}\boldsymbol{I}_1\\\boldsymbol{I}_2\end{bmatrix} \qquad (10)$$

Where $I_1$ is the total current of wire 1 and $I_2$ the total current of wire 2. In a pair of wire, those currents are equal but opposite in directions. $M_{ab}$ is a matrix (size N1 x N2) for the mutual inductances. The solution is done similarly as for (9). The admittance is divided into two parts. The real part is equivalent to $1/R_{12}$ and imaginary part for $1/sL_{12}$. The wire resistance R = 2 * $R_{12}$. In the case of a wire pair, the currents are the opposite, $I_1$ = -$I_2$. But the sign of $M_{ab}$ becomes negative as well, resulting in equation (10).

The number of the mutual inductances is large. As the distance between subconductors increases the proximity effect reduces. The inductance becomes small enough to be ignored. Some authors have studied the issue of ignoring the non-significant components [10] in order to reduce the computing time. Accuracy of the volume fillet method is good and well comparable to FEM-simulation [11].

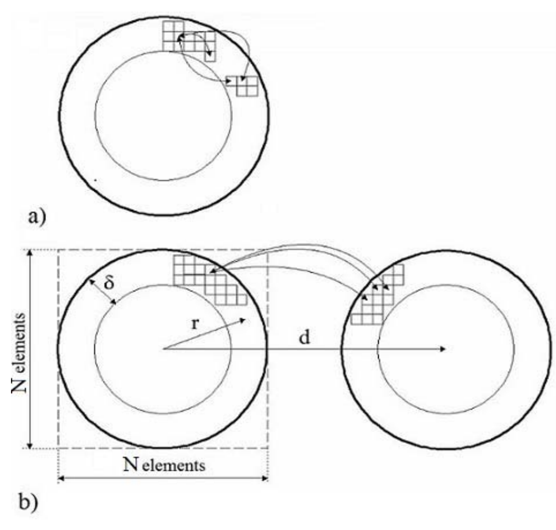


**Figure-3.** Modelling a pair of circular wire. The volume fillet method for case skin effect affects on the effective cross section of the wire. Calculation of a) the self-inductance b) the mutual inductance.

## RESULTS

In this study, no methods for ignoring the non-significant components in volume fillet were implemented. Regardless of this, the needed computing time remains reasonable for the scope of this study. All the calculations

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have been done using Matlab. For these calculations, the rectangular cross section covering the wire cross section has been divided into 900 elements (N=30). The number of those elements including the wire cross section becomes 648. Due to the skin effect the number of cross sections is reducing as shown in Table-1. The calculations were done up to 10 MHz where only 32 elements were left. As the number of elements decreases, the accuracy of the calculations decreases. Matlab calculations for each wire size took approximately 3 minutes. The material properties of PVC have been found in [12]. Some of the calculated results are presented in Figures 3, 4 and in Table-1.

**A. The frequency dependent characteristics of the cable**

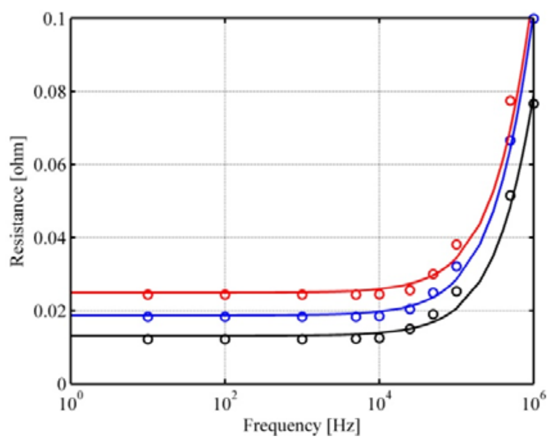


**Figure-4.** The ac resistance [ohm/m] of the wire. The cross sections 0.5 $mm^2$ (red), 1.0 $mm^2$ (blue) and 1.5 $mm^2$ (black).

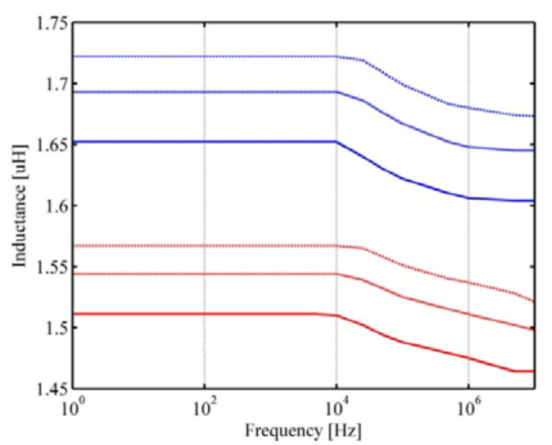


**Figure-5.** The self-inductance $L_s$ (blue) of the wire and the mutual inductance $L_m$ of the wire pair (red). The cross section of the wire 0.5 $mm^2$ (the highest inductance), 1.0 $mm^2$ and 1.5 $mm^2$ (the lowest inductance).

**B. The circuit models for DALI cable**

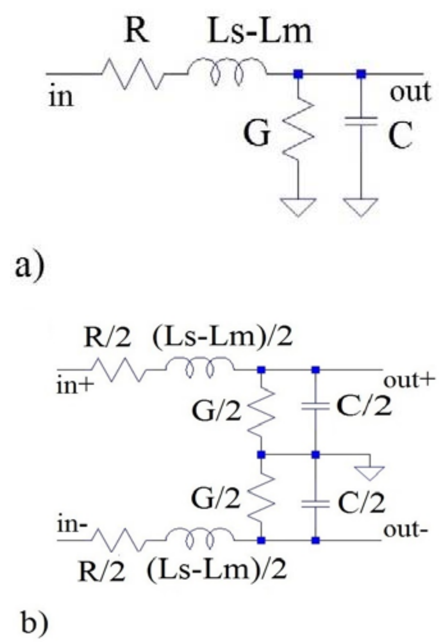


**Figure-6.** The lumped models of the cable. For the used cable R is 12.2 mΩ/m, Ls-Lm is141nH/m, G is 0.1 uS/m, C is 83 pF/m at 1 kHz. Two versions: a) The ground referenced cable, b) The differential cable.

**C. The measured and the simulated results**

The calculated attenuation of the cable is based on the results shown in Table-1. Transfer functions of one and two pole LC-filter have been presented as a reference. As seen in Figure-7 the cable has higher attenuation than one pole low-pass filter's, but less than two pole filters. The lumped model of single LC-stage as shown in Figure-6 is not an accurate model for the cable. In simulations, one could use a two-stage filter instead or a cascade of two single stage filters in a way that the second stage has its pole at bit higher frequency.

Simulations have been done for the interface circuit shown in Figure-1 connected with a lumped cable model shown in Figure-6(b). Cable length is 50 m and conductor cross section is 1.5 $mm^2$. The cable is terminated with another DALI interface circuit. A large overshoot at rising edge is visible. The falling time is very short < 200ns) but there is only a small undershoot. There are no damped oscillations on the falling edge at all. The missing oscillations are related to the underestimated attenuation at higher frequencies.

Simulation efforts were made using a model based on so called "telegraphers equations". These equations fully describe the frequency behaviour of a transmission line. Spice models based on these equations exist [13]. These simulations suffered severe singular matrix problems and exhaustive long simulations times. It

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becomes obvious that those models are mainly for modelling a transmission line with sinusoidal not with pulsed waveforms.

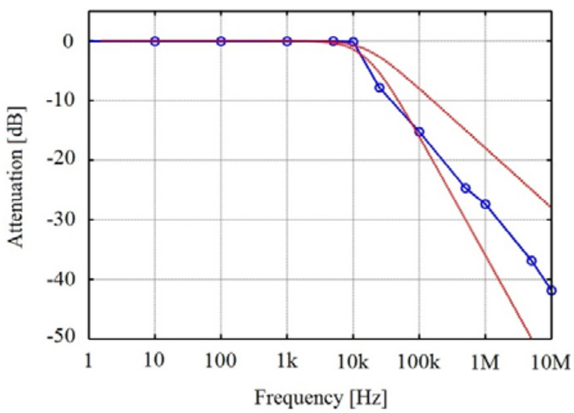


**Figure-7.** Calculated attenuation (dB/m) of 50 m long 1.5 mm$^2$ cable (blue). The transfer functions of one and two pole low-pass filter (red). The cable is ideally terminated.

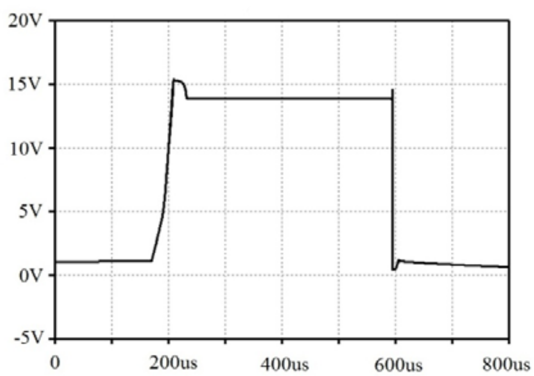


**Figure-8.** The simulated waveform. The lumped model is used for the cable. The length of the cable is 50 m and the cross section is 1.5 mm$^2$. $R_x$ is 100 Ω, $C_x$ is 100 pF.

Figure-9 shows measured waveforms for the case of 50m long cable with conductor cross section of 1.5 mm$^2$. The cable is terminated by another DALI interface circuit. The waveform has a visible overshoot on the rising edge, an undershoot and some dumped oscillation on the falling edge. The rising time is around 20 us, well within the specifications of DALI. A common practice in DALI interface circuits to reduce the overshooting and the oscillations is to add some feedback over the switching component.

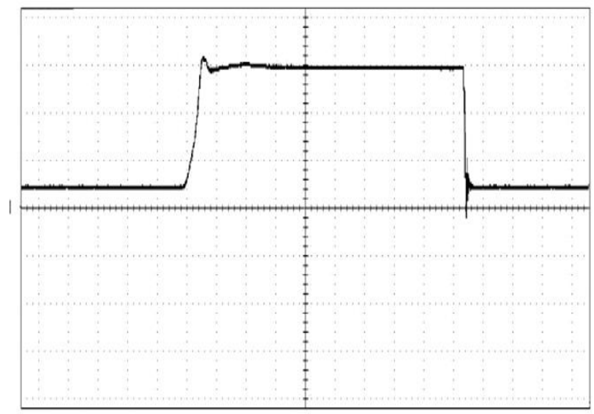

**Figure-9(a).** DALI waveform. Measurements with 50 m 1.5 mm$^2$ cable. $R_x$ is 100, $C_x$ is 100 pF. Horizontal 40 us/div, vertical 5 V/div.

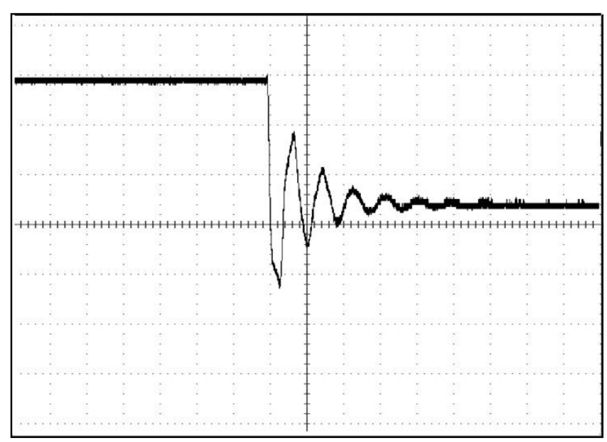

**Figure-9(b).** DALI waveform's falling edge. Measurements with 50 m 1.5 mm$^2$ cable. $R_x$ is 100, $C_x$ is 100 pF. Horizontal 2 us/div, vertical 5 V/div.

In Figure-1 this is done with $R_x$ and $C_x$. $R_x$ is set to 100 Ω. Both experiments and simulations show that practical value for $C_x$ is in range from 100pF to 1nF. While increasing $C_x$, the rising time approaches 100 us, the limit set by DALI standard. The best choice for the switching mosfet would be a type witch has very low $R_{DS(on)}$, preferable < 100 mΩ. In this study IRF640 ($R_{DS(on)}$ typ. 180 mΩ) was used. Optocouplers were type PC123. In case $C_x$ is small the optocoupler may cause the slow rising time of DALI signal. The diode bridge (D1-D4) can also affect on the rising time unless fast schottky diodes are used. A mosfet with low $R_{DS(on)}$ has high input capacitance (Cgs). It is important to arrange a sufficient driver for the mosfet. If there is a slow long lasting ramp on the falling edge, that is normally the consequence of insufficient gate driving. [8] shows waveforms which potentially suffer from this problem. In the interface shown in Figure-1, the driver can be boosted by reducing resistor R4 at the base of Q1.

## CONCLUSIONS

DALI interface circuitry has been designed. The design is made simple, inexpensive and to meet the specifications of DALI standard. The electrical characteristics of the PVC insulated power electrical cable with the twin core and with the conductor cross section in range 0.75 - 1.5 $mm^2$ have been resolved. Self- and mutual inductances and resistance of the cable have been calculated by using the volume fillet method and Matlab software. The results indicate that both the resistance and the inductances remain almost constant below 10 kHz, a decade higher than the fundamental frequency component of DALI signal. The attenuation starts the increase above 10 kHz. The calculated attenuation of the cable is higher than the attenuation of a simple LC-filter stage. The calculated characteristics of the cable have been included in the lumped model of the cable. Spice simulations for the interface and the cable have been conducted. Experimental work included building the interface and measuring it with the load of 50 m cable. The lumped model gives reasonable accurate results. In case better accuracy at higher frequencies is requested, a lumped model with two poles can be used. In Spice simulations, this can be a two-stage filter circuit or just a Laplace statement in a simulation file.

**Table-1.** The calculated electrical parameters of the cable. The cable is PVC insulated wire pair and the cross section of the conductor is 1.5 $mm^2$.

| Freq. [Hz] | Elements | R [mohm]/m | Ls [uH/m] | Lm [uH/m] | G [uS/m] | C [pF/m] |
|---|---|---|---|---|---|---|
| 1 | 648 | 12,20 | 1,652 | 1,511 | 0,10 | 200 |
| 10 | 648 | 12,20 | 1,652 | 1,511 | 0,10 | 183 |
| 100 | 648 | 12,20 | 1,652 | 1,511 | 0,10 | 158 |
| 1 k | 648 | 12,20 | 1,652 | 1,511 | 0,10 | 133 |
| 5 k | 648 | 12,30 | 1,652 | 1,511 | 0,10 | 108 |
| 10 k | 648 | 12,50 | 1,652 | 1,510 | 0,05 | 83 |
| 25 k | 552 | 15,00 | 1,640 | 1,502 | 0,10 | 55 |
| 50 k | 440 | 19,00 | 1,630 | 1,494 | 0,25 | 41 |
| 100 k | 332 | 25,30 | 1,622 | 1,488 | 0,50 | 38 |
| 500 k | 164 | 51,50 | 1,610 | 1,479 | 1,50 | 35 |

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