Proceedings of the ASME 2017 Dynamic Systems and Control Conference
DSCC2017
October 11-13, 2017, Tysons, Virginia, USA

DSCC2017-5377

ON THE MODELING AND ANALYSIS OF AN ENERGY HARVESTER MOVING VIBRATION ABSORBER FOR POWER LINES

Oumar Barry
Central Michigan University
Mt. Pleasant, MI 48858, USA

Mohammad Bukhari
Central Michigan University
Mt. Pleasant, MI 48858, USA

ABSTRACT

Wind-induced vibration of power lines has been a major challenge for design engineers for decades. Hitherto, there is no effective devices that can suppress these vibrations throughout a wide range of resonant frequencies. This paper presents a promising vibration suppression technique using an energy harvester moving vibration absorber (EHMVA), which can simultaneously harvest energy and suppress the vibrations. The vibration-based energy harvesting can be achieved using an electromagnetic transducer, which replaces the viscous damping element of conventional absorbers. This harvested energy can then be utilized to power small sensors and electronic devices required for EHMVA to adapt to wind characteristics and move to an optimum location, thus leading to potentially superior vibration control. The coupled dynamics between a single conductor and EHMVA is presented and numerical examples are carried out to investigate the performance of the proposed absorber. The findings are very promising and open a horizon of future opportunities to optimize the design of EHMVAs for superior performance.

INTRODUCTION

High voltage power lines are often subjected to wind-induced vibration that makes them prone to fatigue failure. For a single conductor, these vibrations take the form of Aeolian vibration and/or galloping, which can be distinguished by their frequency and amplitude of vibration [1]. Aeolian vibration is a low amplitude and high frequency vibration [1] - [10]. It can occur throughout all seasons and across the world. The wind speed usually varies from 1 to 7 m/s exhibiting a frequency between 3 to 150 Hz and maximum peak to peak amplitude slightly less than the conductor diameter (15 to 50 mm) [1]. Galloping mostly occurs in the winter. It is a high amplitude and low frequency vibration caused by steady crosswinds acting upon an asymmetrically iced conductor surface [11] - [23]. The vibration frequency ranges from 0.08 to 3 Hz and the amplitude can be as high as 300 times the conductor diameter [12].

Wind-induced vibration suppression of overhead power lines remains one of the major challenges faced by power utilities. DTE Energy, a Michigan-based utility, recently reported a power outage caused by wind-induced vibration that left more than 4,000 customers without power [21]. Similar power outages due to vibrations were reported in Ontario leaving millions of customers without power [22]-[23]. These unfortunate events can contribute to deaths and billions of dollars in damages [24]-[25].

Conventional protection mechanism against wind-induced vibration is to attach fixed passive vibration absorbers (FPVA) on the conductor. Stockbridge dampers (SD) are the most common devices used for reducing Aeolian vibration [26-28]. Detuning pendulum (DP) or torsional damper detuner (TDD) is generally employed for protection against conductor galloping [11]. The effectiveness of these FPVAs is significantly dependent on the number of resonant frequencies they exhibit, limited to a maximum of four, which is insufficient for suppressing vibrations at all frequencies. The location of these absorbers on the cable is also crucial for achieving superior vibration mitigation. Considerable efforts have been conducted to optimize the placement of these absorbers closer to antinodes [1, 6, 9], but the proposed techniques do not guarantee best performance at every frequency. As the wind speed changes with time, the frequency also changes. This fluctuation causes the location of the absorber to sometimes coincide with a node, resulting in very poor performance.

Another major problem can be attributed with the use of multiple devices for either controlling galloping or Aeolian vibration. Usually these absorbers are clamped to the cable making the lines more prone to fatigue failure. This challenge can be overcome by using either semi-active or active absorbers. However, electrical power is needed to actuate semi-active or active absorbers. So, the fundamental question that arises is then how can this be achieved with minimal economical and environment cost?

In [29] - [32], it has been demonstrated that electrical energy can be harvested from the disturbance and simultaneously be utilized to suppress “bad” vibration in buildings and vehicles. Following this approach, a few number of semi-active or active vibration absorbers can be used for vibration mitigation of both Aeolian vibration and galloping. This will eliminate the requirement of attaching multiple absorbers on the cable. The energy used to power the absorber for semi-active or active absorption can be harvested from the vibration. The harvested energy can then be used to power small sensors and electronic devices for detecting wind

characteristics and moving the absorber to antinodes, thus leading to a smarter and potentially more sustainable vibration control. The proposed absorber is called an energy harvester moving vibration absorber (EHMVA). No modeling or analysis of such devices for controlling wind-induced vibration of power lines is available in the literature. This paper presents the vibration modeling of a single conductor coupled with an EHMVA and analyses the feasibility of simultaneously harvesting energy and suppressing "bad" vibrations. Parametric studies are carried out to investigate the influence of key parameters on the power output and vibration control.

SYSTEM DESCRIPTION

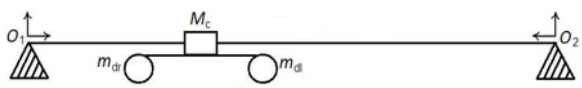

Figure 1: A schematic diagram of conductor with Stockbridge damper

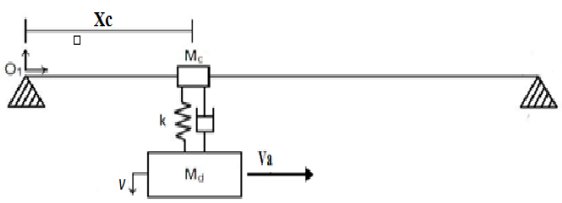

Figure 2: A schematic for a conductor with simplified absorber.

Figure 1 illustrates a schematic diagram for a conductor with moving absorber [3]. The conductor has a length of L, a mass per unit length m, a flexural rigidity of EI, and subjected to an axial tension T. Following [4] the Stockbridge damper can be simplified to mass-spring-mass-damper system as shown in Figure 2. This equivalent system has in-span mass m_c, equivalent stiffness k, equivalent damping coefficient c, and equivalent suspended mass m_d. The damper in Figure 2 is replaced by an electromagnetic transducer shunted with a circuit including a capacitor, an AC-DC converter, a DC-DC converter, energy storage elements and electric loads. This system can be modeled as a transducer with an RLC circuit [31-32]. The circuit has a capacitance denoted by C, inductance denoted by L, and a resistance denoted by R. A schematic of the system is shown in Figure 3.

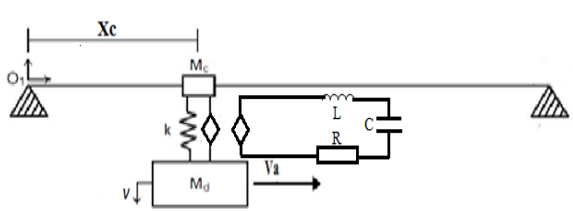

Figure 3: Replacing the damper by electromagnetic transducer with RLC circuit.

MATHEMATICAL MODEL

The dynamic equations for the system in Figure 3 can be expressed as

$$EI\frac{d^4y}{dx^4} + m\frac{d^2y}{dt^2} + T\frac{d^2y}{dx^2} = F(x,t) - (F_1 + F_2)G(x,t) \tag{1}$$

$$m_a\frac{d^2v}{dt^2} - F_2 = 0 \qquad x \in (0,L), t > 0 \tag{2}$$

$$L\ddot{q} - k_v\left(\frac{\partial y(x_c,t)}{\partial t} - \dot{v}\right) + R\dot{q} + \frac{1}{C}q = 0 \tag{3}$$

where y denotes the displacement of the beam, v is the absolute displacement of in-span mass, $\dot{q}$ is the electrical current in the electromagnetic transducer, F_1 and F_2 are defined as

$$F_1 = m_c\left(\frac{\partial^2 y}{\partial t^2}\right) \tag{4}$$

$$F_2 = k(y(x_c,t) - v) + k_f\dot{q} \tag{5}$$

k_f represents the force coefficient, k_v is the voltage constant of the electromagnetic transducer, and $G(x,t)$ is the motion profile of the moving absorber. This profile can be defined for two absorbers moving forwards and backwards along 10% of the total length of the beam as

$$\begin{aligned} G(x,t) = {} & \delta(x - V_a t)H\left(0.1\frac{L}{V_a} - t\right) \\ & + \delta(x - (.2L - V_a t))H\left(t - 0.1\frac{L}{V_a}\right)H\left(0.2\frac{L}{V_a} - t\right) \\ & + \delta(x - (L - V_a t))H\left(0.1\frac{L}{V_a} - t\right) \\ & + \delta(x - (1.1L - V_a t))\,H\left(t - 0.1\frac{L}{V_a}\right)H\left(0.2\frac{L}{V_a} - t\right) \end{aligned} \tag{6}$$

where H is the Heaviside function. The boundary conditions and the initial conditions of the dynamic system are given as

$$y(0,t) = 0; \quad y(l,t) = 0; \quad \frac{\partial^2 y}{\partial x^2}(0,t) = 0; \quad \frac{\partial^2 y}{\partial x^2}(L,t) = 0; \tag{7.a}$$

$$y(x,0) = 0; \quad \frac{\partial y}{\partial t} = 0; \tag{7.b}$$

$$v(0) = 0; \quad \frac{dv}{dt} = 0; \tag{7.c}$$

$$q(0) = 0; \quad \frac{dq}{dt} = 0; \tag{7.d}$$

Following Ref. [3], the wind force in Eq. (1) is given by

$$F(x,t) = f_0 \sin\omega t \tag{8}$$

where ω is the excitation frequency and f_0 is the drag force.

The solution of transverse vibration of beam can be

expressed using the following eigenfunction expansion

$$y(x,t) = \sum_{r=1}^{\infty} \Phi_r(x) A_r(t) \tag{9}$$

where $A_r(t)$ is unknown function of time and $\Phi_r(x)$ is the mode shape of the bare beam subjected to axial tension. The mode shape is defined as

$$\Phi_r(x) = \sqrt{\frac{2}{ml}} \sin\left(\left(\sqrt{\frac{-T}{2EI} + \sqrt{\frac{T^2}{4(EI)^2} + \frac{m\omega_r{}^2}{EI}}}\right) x\right) \tag{10}$$

where ω_r refers to the natural frequencies of the conductor, and it can be obtained as

$$\omega_r = \left(\frac{\pi}{L}\right)^2 \sqrt{\frac{EI}{m}\left(r^4 + \frac{r^2 T L^2}{\pi^2 EI}\right)} \tag{11}$$

Introducing the eigenfunction expansion in Eqs. (1)-(3) yields

$$EI \sum_{k=1}^{\infty} \frac{d^4 \Phi_k}{dx^4} A_k + T \sum_{k=1}^{\infty} \frac{d^2 \Phi_k}{dx^2} A_k + m \sum_{k=1}^{\infty} \Phi_k \frac{d^2 \mathrm{A}_k}{dt^2} = -[m_c (\sum_{k=1}^{\infty} \Phi_k \frac{d^2 \mathrm{A}_k}{dt^2})_{x=d} + k(\sum_{k=1}^{\infty} \Phi_k A_k - v)_{x=d} + k_f \dot{q}]\, G(t) + F(x,t) \tag{12}$$

$$m_a \ddot{v}(t) - k(\sum_{k=1}^{\infty} \Phi_k A_k - v)_{x=d} - k_f \dot{q} = 0 \tag{13}$$

$$L\ddot{q} - k_v(\sum_{k=1}^{\infty} \Phi_k \dot{A}_k - \dot{v})_{x=d} + R\dot{q} + \frac{1}{C} q = 0 \tag{14}$$

where d refers to the position of the absorber.

Multiplying Eq. (12) by $\Phi_i(x)$, integrating the resulting equation over the length, and applying the orthogonality condition, the following system of ordinary differential equations can be obtained

$$\ddot{A}_p(t) + M_c \left[\sum_{r=1}^{\infty} \ddot{A}_r(t) \Phi_r(d)\right] \mathrm{D}_p(\mathrm{t}) + \omega_p^2 A_p(t) + \{k \left[\sum_{r=1}^{\infty} A_r(t) \Phi_r(d) - v(t)\right] + c k_f \dot{q}\} D_p(t) = N_p(t) \tag{15}$$

where $N_p(t)$ and $D_p(t)$ are given by:

$$N_p(t) = \int_0^L \Phi_r(x) F(x,t) dx, r = 1,2, \ldots.. \tag{16}$$

$$D_p(t) = \int_0^L \Phi_r(x) G(x,t) dx, r = 1,2, \ldots.. \tag{17}$$

The harvested energy by EHMVA can be expressed as

$$E = \int_0^{t_1} \mathrm{R} \dot{q}^2 dt \tag{188}$$

where t_1 is the time needed by the absorber to travel one full cycle (i.e., forward and backward).

NUMERICAL RESULTS

The system of ordinary equations, Eqs. (13)-(15) are solved numerically using Matlab. The numerical simulation is carried out using the optimum values of the shunted RLC circuit that were obtained in [31-32]. These values along with the values of the conventional conductor-Stockbridge damper parameters are listed in Table I.

TABLE I Key parameters

Parameter	Value
L *(m)*	27.25
EI *(N.m²)*	1602
k_v *(V/(m/s))*	12.6
k_f *(N/A)*	12.6
m *(kg/m)*	1.6286
T *(N)*	27,840
f_0 *(N/m)*	0.432
m_c *(kg)*	0.2
k *(N/m)*	1,027.1
v_a *(m/s)*	0.1
R *(Ω)*	22.42
L *(H)*	1.496
C *(F)*	0.003

Figure 4 illustrates the maximum displacement (transient response) for different frequency values and different types of absorbers. The results show that the transient response is not significantly affected by switching from fixed absorber to

EHMVA. However, in terms of residual vibrations (i.e., steady state vibrations) EHMVA shows a much superior performance, as shown in Figure 5.

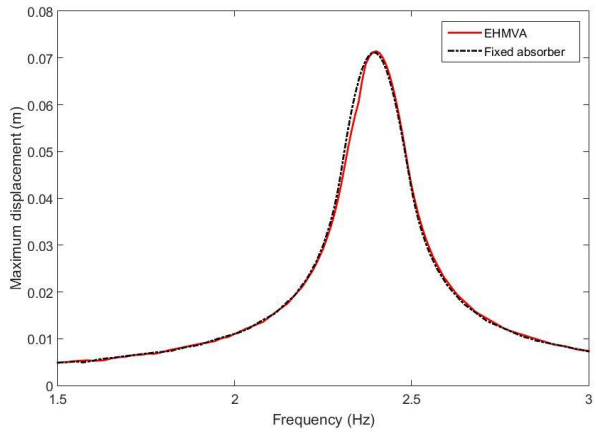

Figure 4: Maximum displacement of the conductor for different types of absorber.

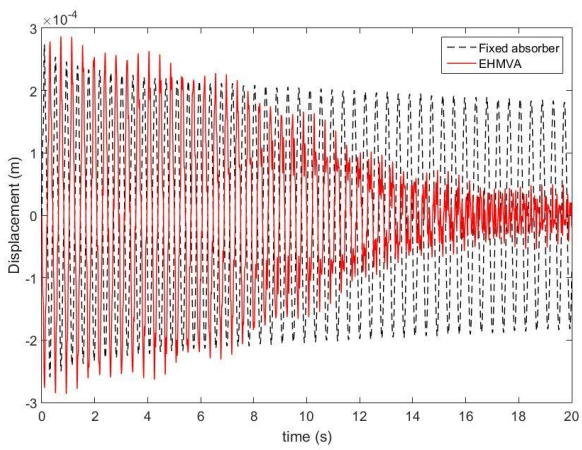

Figure 5: Reduction in residual vibrations due to using EHMVA, ω=20 Hz.

Figure 6 shows the effect of the voltage constant of the transducer on the maximum displacement of the beam. The results show that the maximum vibration displacement is slightly affected by the voltage constant, in that it increases with increasing voltage constant. The role of the voltage constant on the maximum displacement of the conductor is depicted in Figure 7. It is observed that vibration amplitude significantly increases with increasing voltage constant.

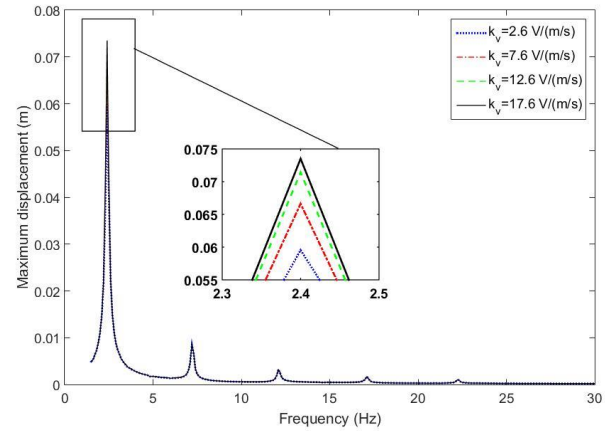

Figure 6: The effect of changing k_v on the maximum displacement of the beam.

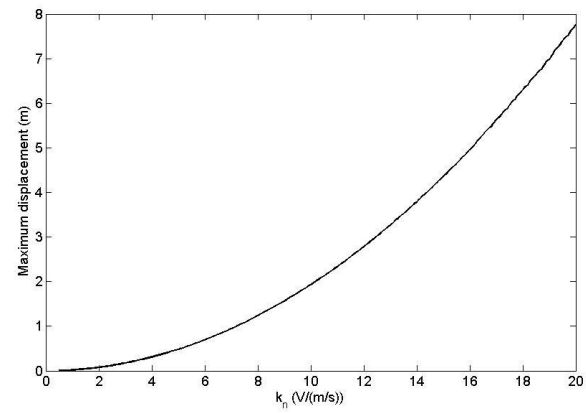

Figure 7: Maximum vibration amplitude of the conductor during one cycle of absorber motion with variable voltage constant.

Figures 8 and 9 illustrate the effect of the inductance on the maximum displacement and harvested energy, respectively. The results indicate that increasing the inductance mitigates the maximum displacement. However, this increase is accompanied by a significant reduction in the harvested energy as demonstrated in Figure 9.

The role of the velocity of EHMVA on the harvested power is depicted in Figure 10. The results indicate that the power can be significantly affected by the velocity of the proposed absorber.

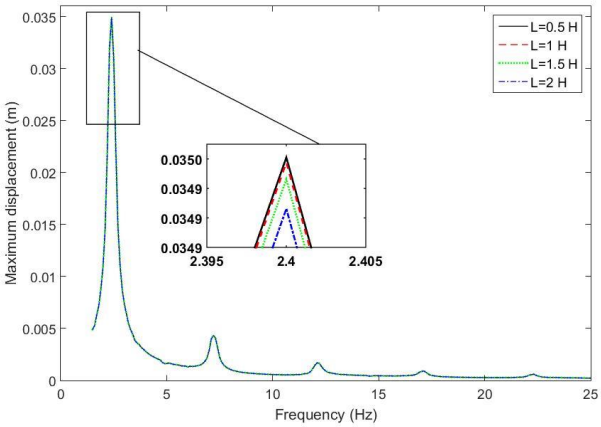

Figure 8: The effect of changing the inductance on the maximum displacement.

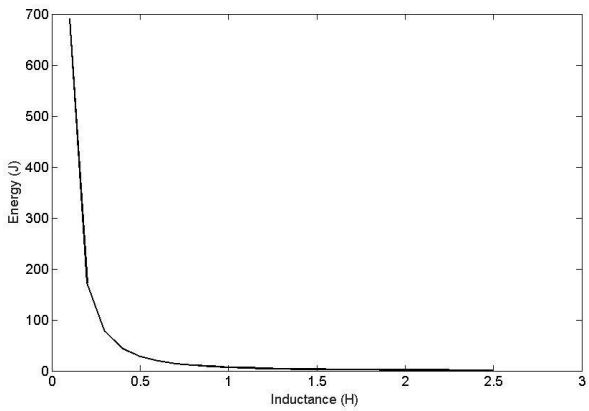

Figure 9: Harvested energy by the electromagnetic system during one cycle of absorber motion with variable inductance.

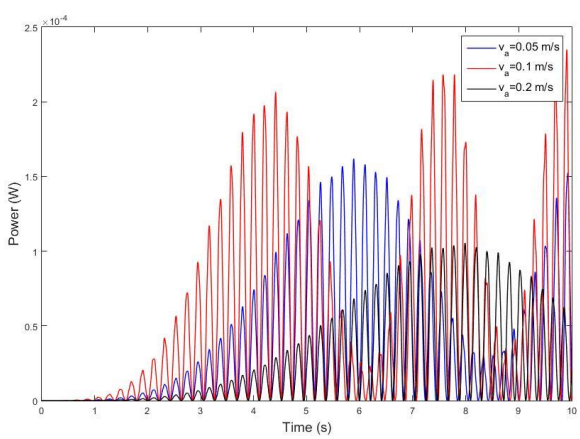

Figure 10: The harvested power for different absorber speed.

CONCLUSION

This paper presents the modeling and analysis of a vibration absorber capable of simultaneously harvesting energy and suppressing vibration of overhead power lines. The viscous damping element of the conventional Stockbridge damper is replaced by an electromagnetic transducer shunted with an RLC circuit. The coupled dynamic between the conductor and the absorber is presented. Numerical examples are conducted to ascertain the feasibility of harvesting energy and suppressing vibration. The results indicate that significant energy can be harvested from the vibrating conductor. However, the amount of harvested energy significantly depends on key parameters such as velocity of the moving absorber, voltage constant, and inductance. The results also demonstrate that superior vibration suppression can be achieved by the energy harvester moving vibration absorber (EHMVA). The magnitude of vibration suppression, however, is also dependent on key parameters. The findings in this paper provide fundamental insights about the potential of the proposed absorber to control both Aeolian vibration and galloping of overhead power lines and pave the way for future research to optimize the performance of EHMVA.

REFERENCES

[1] EPRI., 2006. "*Transmission line reference book, wind induced conductor motion*," Palo Alto, California: Electrical Power Research Institute.

[2] O. Barry, J. Zu, and D. C. Oguamanam, "Analytical and experimental investigation of overhead transmission line vibration," Journal of Vibration and Control, vol. 21, 2015, pp. 2825-2837.

[3] O. Barry, J. W. Zu, and D. C. D. Oguamanam, "Forced vibration of overhead transmission line: analytical and experimental investigation," *Journal of Vibration and Acoustics*, vol. 136, 2014, 041012.

[4] O. Barry, R. Long, and D. C. D. Oguamanam, " Simplified vibration model and analysis of a single-conductor transmission line with dampers," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2016, 0954406216660736.

[5] O. Barry, J. W. Zu, and D. C. D. Oguamanam, "Nonlinear dynamics of Stockbridge dampers," *Journal of Dynamic Systems, Measurement, and Control*, vol. 137, 2015, 061017.

[6] O. Barry, R. Long, and D. C. D. Oguamanam, "Rational damping arrangement design for transmission lines vibrations: analytical and experimental analysis," *Journal of Dynamic Systems, Measurement and Control*, vol. 139, 2017, 051012.

[7] R. Claren and G. Diana, "Mathematical analysis of transmission line vibration," *Institute of Electrical and Electronics Engineers, Transactions on Power Apparatus and Systems*, vol. 60, 1969, pp. 1741-1771.

[8] M. L. Lu and J. K. Chan, "An efficient algorithm for Aeolian vibration of single conductor with multiple dampers," *Institute of Electrical and Electronics Engineers, Transactions on Power Delivery*, vol. 22, 2007, pp. 1822-1829.

[9] J. Vecchiarelli, I. G. Curries, and D. G. Havard, "Computational analysis of Aeolian conductor vibration with a stockbridge-type damper," *Journal of Fluid and Structures*, vol. 14, 2000, pp. 489-509.

[10] B. Shafer, "Dynamic modeling of wind induced vibration of overhead lines," *Int. Non Linear Mechanics*, vol. 19, 1984, pp. 455-467.

[11] J. Wang, "Overhead transmission line vibration and galloping," *IEEE International Conference on High Voltage Engineering and Application, Chongqing, China, November 9-13*, 2008, PP 120-123.

[12] C. B. Rawlins, “Analysis of conductor galloping field observations-single conductors,” *IEEE Transactions on Power Apparatus and Systems*, vol. 8, 1981, pp.3744-3753.

[13] D. G. Havard, and J. C. Pohlman. "Five years' field trials of detuning pendulums for galloping control," *IEEE transactions on power apparatus and systems*, vol. 2, 1984 pp. 318-327.

[14] C. B. Rawlins, “Analysis of conductor galloping field observations-single conductors,” *IEEE Transactions on Power Apparatus and Systems*, vol. 8, 1981, pp. 3744-3753.

[15] C. B. Rawlins, "Conductor galloping field observation analysis update," *ALCOA Conductor Products Company. Technical note* 26 (1986).

[16] Z. Yan, Z. Li, E. Savory, and W. E. Lin, “Galloping of a single iced conductor based on curved-beam theory,” Journal *of Wind Engineering and Industrial Aerodynamics*, vol. 123, 2013, pp. 77-87.

[17] Z. Yan, Z. Li, E. Savory, and W. E. Lin, “Galloping of Iced Quad-conductor based on curved-beam theory,” *Journal of Sound and Vibration*, vol. 333, 2014, pp. 1657-1670**.**

[18] V. H. Pham, H. Yamaguchi, M. Isozaki, snd J. H. Gull, “Large amplitude vibrations of long-span transmission lines with bundled conductors in gusty wind,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 126, 2014, pp. 48-59.

[19] P. Van Dyke, and A. Laneuville, “Galloping of a single conductor covered with a D section on a high-voltage overhead test line,” *J. Wind Eng. Ind. Aerod*, vol. 96, 2008, pp. 1141–1151.

[20] C. B. Gurung, H. Yamaguchi, and T. Yukino, "Identification and characterization of galloping of Tsuruga test line based on multi-channel modal analysis of field data," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 91, 2003 pp. 903-924.

[21] L. Li, H. Cao, K. Ye, and Y. Jiang, "Simulation of galloping and wind-induced vibration control," *Noise & Vibration Worldwide*, vol. 41, 2010, pp. 15-21.

[22] L. Kollár, M. Farzaneh, and P. Van Dyke, "Modeling ice shedding propagation on transmission lines with or without interphase spacers," *IEEE Transactions on Power Delivery* vol. 28, 2013, pp. 261-267.

[23] N. A. Saadabad, N. Asmari, H. Moradi, and G. Vossoughi, "Semi-active control of forced oscillations in power transmission lines via optimum tuneable vibration absorbers: with review on linear dynamic aspects," *International Journal of Mechanical Sciences*, vol. 87 2014, pp. 163-178.

[24] CBS Detroit “4,000 DTE Customers Remain Without Power Nearly A Week After Damaging Winds”, March 14th 2017, http://detroit.cbslocal.com/2017/03/14/7000-dte-customers-remain-without-power-nearly-a-week-after-damaging-winds/.

[25] D. Havard, "Conductor Fatigue and Damper Damage on the Sarnia-Scott TS x Lucasville JCT." *Toronto, Ontario* 2005, 1996.

[26] D. Havard. Assessment of the Cowal JCT x Longwood TS for vibration control, *Toronto, Ontario*, 2008. Technical paper.

[27] University of Denver professor: New transmission line product would save lives; http://www.bizjournals.com/denver/printedition/2013/05/24/university-of-denver-professor-new.html?page=all

[28] The blackout of 2003: The overview; power surge blacks out northeast, hitting cities in 8 states and Canada; midday shutdowns disrupt millions, August 15th 2003, New York Times. http://www.nytimes.com/2003/08/15/nyregion/blackout-2003-overview-power-surge-blacks-northeast-hitting-cities-8-states.html

[29] L. Zuo and X. Tang. "Large-scale vibration energy harvesting," *Journal of intelligent material systems and structures*, vol. 24, 2013 pp. 1405-1430.

[30] X. Tang and L. Zuo. "Simultaneous energy harvesting and vibration control of structures with tuned mass dampers," *Journal of Intelligent Material Systems and Structures*, vol. 23, 2012 pp. 2117-2127.

[31] Liu, Yilun. "Design, Modeling and Control of Vibration Systems with Electromagnetic Energy Harvesters and their Application to Vehicle Suspensions." PhD diss., Virginia Tech, 2016.

[32] Tang, Xiudong. "Simultaneous Energy Harvesting and Vibration Control of Tall Buildings using Electricity-Generating Tuned Mass Dampers." PhD diss., State University of New York at Stony Brook, 2013.