DIVIDE AND CONQUER STRATEGIES FOR ENHANCED RESILIENCY IN ELECTRICAL TRANSMISSION LINES

Shaleena Jaison [1], D. Subbaram Naidu[2] and Jake P. Gentle[3]

[1] Idaho State University, 921 South 8th Avenue, Pocatello, Idaho, U.S.A

[1] Email: jaisshal@isu.edu; Ph: +1(208)220-6602

[2] University of Minnesota Duluth, 1023 University Drive, Duluth, Minnesota, USA

[2] Email: dsnaidu@d.umn.edu ; URL: http://www.d.umn.edu/~dsnaidu

[3] Idaho National Laboratory, Idaho Falls, Idaho, U.S.A

[3] Email: jake.gentle@inl.gov

Abstract

With the modernization of the existing electric grid with smart grid technology, overhead power transmission lines have to be monitored in real-time to meet energy demands. Even though smart control and decision making characterize this technology, it's increasing dependence on cyber infrastructure makes its vulnerable to cyberattacks. The control strategies in place have to protect the transmission system from perturbations/faults as well as be resilient to cyber-attacks. In this paper, an optimal control scheme is presented that mitigates perturbations in a transmission line (TL) and is resilient to outages/attacks. This design exploits the inherent time scale nature of transmission lines. Time Scale Analysis methods are applied to decouple the slow and fast dynamics in a TL, resulting in lower order, slow and fast subsystems. Linear Quadratic Regulators are designed separately for each subsystem. The simulations compare the proposed method to a full order system and also check the stability of the control design in the event of failures. The results manifest the effectiveness of the proposed method, which provides comparable control with reduced order subsystems, and also provide stability of the transmission system in the absence/failure of one of the controllers.

1 INTRODUCTION

The energy demands of the modern world and extreme weather conditions have brought about high stresses on the existing energy infrastructure. Power outages due to severe weather conditions are likely to increase in the future as the climatic changes are altering the frequency and intensity of natural events [U.S. DOE, August 2013]. These growing concerns have led to the research and development of smart electric grids which could provide real time monitoring and control of the existing power resources.

Decisions to manage power, such as diverting excess power from a less demand to a high demand area, increasing ampacity levels of existing transmission lines based on real-time weather conditions [Gentle, *et.al.* 2015], etc. will be part of controller strategies to meet daily power demands. Safety and stability of the power system has to be ensured at all times, and this requires the controller to mitigate any perturbations or faults in the transmission line (TL) and return power to nominal levels. With smart grid technology, software control and decision making becomes deeply integrated into the electric power system. However, the increased dependence on cyber infrastructure makes it vulnerable to malicious cyber-attacks. Hence, to improve the security of the smart grid, control strategies have to be devised that are resilient to faults and malicious attacks.

In this paper, an optimal control design is proposed that mitigates perturbations in a TL, and which incorporates resiliency as part of its design. The resiliency arises from having a decentralized control scheme with multiple controllers instead of one central controller, thereby ensuring the stability of the whole system in the event of failure of one of the controllers. This control realization is possible due to the slow-fast behaviour of the TL dynamics.

The organization of this paper is as follows: Section 2 presents time domain modelling of transmission lines, which captures the electrical and thermal dynamics in a TL. The slow-fast dynamics is verified through state response plots and linearizations. In Section 3, Time Scale Analysis is carried out where the full order TL system is decoupled into slow and fast subsystems, independent of each other. LQR design using time scales is presented in Section 4 where controllers for mitigating system perturbations, are designed separately for each subsystem. Section 5 presents the results and conclusions of the proposed LQR for perturbation control and system stability in the event of failure of one of the controllers.

2 TIME DOMAIN MODELING OF TRANSMISSION LINES

A non-linear model of a TL is provided in this section. A short length line, described using a lumped parameter model, is considered for analysis and its equivalent circuit is as shown in Figure 1. The resistance of the transmission line, R is a function of conductor temperature, T_{avg} and it determines the amount of current flowing through the line.

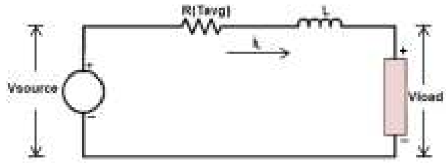

Figure 1. *Equivalent circuit of a short-length transmission line*

Transmission lines are subjected to various events in the field. Few of which that cause a noticeable impact are, current flow in the line, heating effects due to line resistance, weather effects on the line, for example cooling due to wind flow or heating due to increase in ambient temperature. The temperature dynamics in a TL is well described in the IEEE Standard 738 [IEEE-738, 2012]. However, it fails to address the line current dynamics that occurs simultaneously with the temperature dynamics. In this model, a TL is modeled as a complex system where both the line current dynamics and temperature dynamics are simultaneously present and interact with each other. The current dynamics is described using Kirchoff's current and voltage laws, while the temperature dynamics is described using [IEEE-738, 2012]. The state space model is provided in (1) as,

$$\begin{aligned} \frac{di_L(t)}{dt} &= -i_L(t)\frac{R(T_{avg})}{L} - i_L(t)\frac{R_{load}}{L} + \frac{v_{source}}{L}, \\ \frac{dT_{avg}(t)}{dt} &= \frac{1}{mC_p}\left[R(T_{avg}(t))i_L^2(t) + q_s - q_c - q_r\right], \end{aligned} \tag{1}$$

where $i_L(t)$ is the current flowing through the circuit, $T_{avg}(t)$ is the average temperature of the line conductor which depends on the line current (i_L), solar heat gain (q_s), convection heat loss (q_c) and radiation heat loss (q_r). m is mass per unit length of the conductor, C_p is the specific heat of the conductor material, L is the line inductance, R_{load} is a resistive load at the receiving end of the line, and v_{source} is the source voltage. The definitions of $R(T_{avg})$, (q_s), (q_c) and (q_r) are defined in the [IEEE-738,2012]. The nonlinear model in (1) is expressed in the standard nonlinear form, $\dot{\boldsymbol{x}} = f(\boldsymbol{x},\boldsymbol{u})$, where the state vector $\boldsymbol{x}$ and input vector $\boldsymbol{u}$ are,

$$\boldsymbol{x} = \begin{bmatrix} i_L & T_{avg} \end{bmatrix}^T, \ \boldsymbol{u} = \begin{bmatrix} v_s \end{bmatrix} \tag{2}$$

2.1 Analysis of the Transmission Line Model

The nonlinear model was simulated to capture the time scale nature of transmission lines. The system was perturbed by a step change in source voltage at the origin, and the state responses were observed. The plots of states with respect to time are displayed in Figure 2.

It was observed that the line current's step response was much faster than that of the line temperature. Observing the rise time of current near the origin, revealed it to be in the order of milliseconds, while that of temperature was in the order of minutes. This difference in the speed of variables indicates the presence of two time scales in the system, one slow and one fast. To further investigate, the nonlinear system was linearized about various operating points and the eigenvalues were evaluated. The results are tabulated in Table 1. The clearly distinct eigenvalues at any time instant signifies that transmission lines exhibit time scales, where the line current dynamics operate on a fast time scale and the temperature dynamics operate on a slower time scale.

Since time scale behaviour was observed, a transmission line is an ideal candidate for Time Scale Analysis. In the following section, the full order transmission line model is decoupled into lower single order, slow and fast subsystems, for which separate LQR controllers are designed.

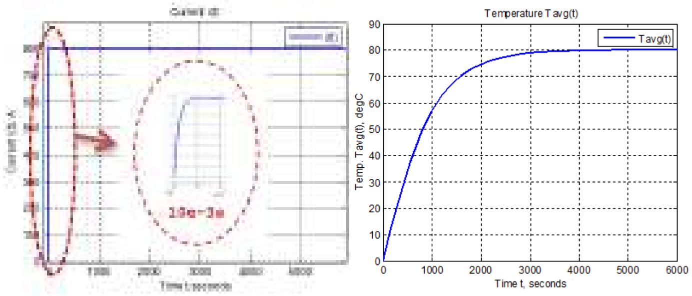

Figure 2. *Response of line current and line temperature to a step change*

Table 1. *Linearization of transmission line model at various time instants*

Time instant	Eigenvalues
t = 0s	-2.6561*10^3; -2.6102*10^-4
t = 1000s	-2.6682*10^3; -1.4177*10^-3
t = 2000s	-2.6712*10^3; -1.4478*10^-3
t = 3000s	-2.6719*10^3; -1.4551*10^-3
t = 6000s	-2.6866*10^3; -1.4901*10^-3

Singular Perturbation and Time Scale Analysis methods are well recorded in literature and its applications span various fields of engineering. These methods offer model order reduction and significant computational savings, which facilitates online implementation of controllers [Naidu D. S., 2002].

3 TIME SCALE ANALYSIS METHOD

A brief description of the decoupling process into a slow and fast subsystem [Naidu & Calise, 2001] is mentioned below.
The nonlinear model in Section 2 is linearized about an operating point as,

$$\begin{aligned} \dot{x}_1 &= A_{11}x_1 + A_{12}x_2 + B_{11}u, \\ \dot{x}_2 &= A_{21}x_1 + A_{22}x_2 + B_{21}u, \end{aligned} \tag{3}$$

Where x_1 and x_2 are the *m*- and *n*- dimensional state vectors, *u* is an *r*-dimensional control vector, and matrices A_{ij} and B_{ij} are of appropriate dimensions. This linear system should have widely separated groups of eigenvalues.

3.1 Decomposition of System Dynamics

A two-stage linear transformation [Naidu & Calise, 2001], given by

$$x_s = x_1 - Mx_f,\; x_f = x_2 + Lx_1, \tag{4}$$

is applied on the system in (3) to decouple it into independent slow and fast subsystems,

$$\begin{aligned} \dot{x}_s(t) &= A_s x_s(t) + B_s u(t), \\ \dot{x}_f(t) &= A_f x_f(t) + B_f u(t), \end{aligned} \tag{5}$$

where,

$$\begin{aligned} A_s &= A_1 - A_2L, & A_f &= A_4 + LA_2, \\ B_s &= B_1 - MLB_1 - MB_2, & B_f &= B_2 + LB_1. \end{aligned} \tag{6}$$

The subscripts 's' and '*f*' denote slow and fast states respectively. The matrices A_1 to A_4 and B_1 to B_2 are obtained from the equations in (3) as,

$$A_1 = A_{11},\; A_2 = A_{12},\; B_1 = B_{11},\; A_3 = A_{21},\; A_4 = A_{22},\; B_2 = B_{21}. \tag{7}$$

The variables $L(n \times m)$ and $M(m \times n)$ are solutions of the nonlinear Lyapunov-type equations,

$$\begin{aligned} LA_1 + A_3 - LA_2L - A_4L &= 0, \\ (A_1 - A_2L)M - M(A_4 + LA_2) + A_2 &= 0. \end{aligned} \tag{8}$$

which are calculated iteratively using the high accuracy Newton method [Gajic & Lim, 2001]. It is evident from

(5) that the state variables x_s and x_f can be solved independently of each other. In the full order system, the slow and fast dynamics interact with each other which causes 'stiffness' in computations. The decoupled systems are relieved of 'stiffness' and hence provide significant computational savings.

3.2 Time Scale Analysis Results

On linearizing the model equations in (1) about a nominal operating point, 2^{nd} order system matrices were obtained.

$$A=\begin{array}{c}\begin{array}{cc} A_1 & A_2\end{array}\\ \begin{bmatrix}-2687 & -485.3\\ 0.0001684 & -0.001462\end{bmatrix}\\ \begin{array}{cc}A_3 & A_4\end{array}\end{array};\ B=\begin{array}{c}B_1\\ \begin{bmatrix}25.39\\ 0\end{bmatrix}\\ B_2\end{array}$$

L and *M* were calculated iteratively using Newton's Algorithm. The 1^{st} order decoupled matrices were found to be,

$$A_s=\left[\text{ -2687}\right];\ A_f=\left[\text{-0.0010289}\right] \qquad B_s=\left[25.39\right];\ B_f=\left[\text{-2.2658e-05}\right]$$

To ensure that the decoupled systems retain the slow and fast dynamics, the eigenvalues of the full order and reduced order systems were compared. The eigenvalues are provided in Table 2. The results confirm that the time scale method decouples the system dynamics almost perfectly. The accuracy parameter of Newton's algorithm could be adjusted to get the exact same eigenvalues for both the systems.

Table 2. *Comparison of full order and reduced order eigenvalues*

Full Order	**Eigenvalues**
A	eig(A) = -2687; -0.0014924
Reduced Order	**Eigenvalues**
A_s - slow subsystem	eig A_s = -2687
A_f - fast subsystem	eig A_f = -0.0010289

4 OPTIMAL CONTROL DESIGN

In general, an optimal controller provides the best possible performance for a given performance index or cost function. When the performance index is quadratic, and the optimization is over an infinite horizon, the resulting optimal control law obtained by minimizing the cost function is called Linear Quadratic Regulator (LQR). Transmission lines are subjected to perturbations arising from sudden loading effects by a set of electric motors, or a lightning strike to the line, or an abrupt change in the source voltage. In such events, the objective of an LQR control is to bring the perturbed states to zero. It is assumed that all the states are measurable and the control signal is unconstrained for design purposes. The performance index is chosen to minimize the error between the perturbed state and the desired state (which is zero) for an infinite time period.

4.1 LQR Control Design

Generally, the standard LQR design for any full order system does not separate the slow and fast dynamics. Here we propose a LQR design for the decoupled transmission line where control laws are implemented separately for the slow and fast subsystems [Jaison *et.al.*, 2014].

The slow subsystem x_s defined in (5), has a performance index,

$$J_s=\frac{1}{2}\int_{t_0}^{\infty}\left[x_s^T(t)Q_s x_s(t)+u_s^T(t)R_s u_s(t)\right]dt, \tag{9}$$

where Q_s and R_s are the weighting matrices for the slow subsystem. The control signal $u_s^*(t)$ for the slow subsystem is calculated as:

$$u_s^*(t)=-K_s x_s(t)=-R_s^{-1}B_s^T P_s x_s(t), \tag{10}$$

where K_s is the regulator gain of the slow subsystem and P_s is the solution of the slow algebraic Riccati equation,

$$P_s A_s+A_s^T P_s+Q_s-P_s B_s R_s^{-1}B_s^T P_s=0. \tag{11}$$

Similarly for the fast subsystem, the LQR control is calculated as,

$$u_f^*(t)=-K_f z_f(t)=-R_f^{-1}B_f^T P_f x_f(t). \tag{12}$$

where P_f is the solution of the fast algebraic Riccati equation,

$$P_f A_f + A_f^T P_f + Q_f - P_f B_f R_f^{-1} B_f^T P_f = 0. \tag{13}$$

A block diagram describing LQR control design for the reduced order transmission line is presented in Figure 3. The feedback control is a composite control $u^*(t)$ i.e. sum of slow control $u_s^*(t)$ and fast control $u_f^*(t)$.

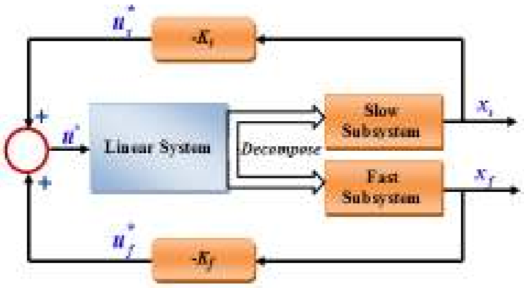

Figure 3. *LQR control design for reduced order linear transmission line*

4.2 Resilience of LQR Control with Time Scale Approach

Resilience of controller operation is of paramount concern in today's highly interconnected and networked society. In the event of a cyber-attack or failure of a controller, especially for critical and sensitive applications, implementing a decentralized control scheme will be highly beneficial. This would guarantee some control action to be still in place which would avoid critical failure of the entire system. In the event of controller outages, it may be possible to control the plant/system using any one of the multiple controllers designed. Such a control system designed to tolerate failures of controllers, while retaining desired control system properties, is a "reliable" control system.

The decoupling of slow and fast dynamics in a transmission line facilitates implementation of a decentralized control scheme. Here, it is shown how a single controller (either slow or fast) by itself gives nearly original performance, thereby making the system more reliable or 'resilient' in case of either controller malfunction.

The linear transmission line was tested for three cases:

- Control signal = slow control + fast control
- Control signal = only slow control
- Control signal = only fast control

5 RESULTS & CONCLUSIONS

All the controllers were designed in MATLAB® and implemented in Simulink®. Model data for simulations were taken from [IEEE-738, 2012] for a 795 kcmil 26/7 Drake ACSR conductor.

5.1 Results of LQR Control

Matrices A_s , B_s , A_f and B_f for LQR control design were provided in Section 3.2. The weighting matrices Q_s , R_s , Q_f and R_f were chosen such that they minimize the time taken by the states to get to zero. These matrices were chosen from multiple iterations. A comparison between the full order and reduced order control of linear transmission line is provided in Figure 4.

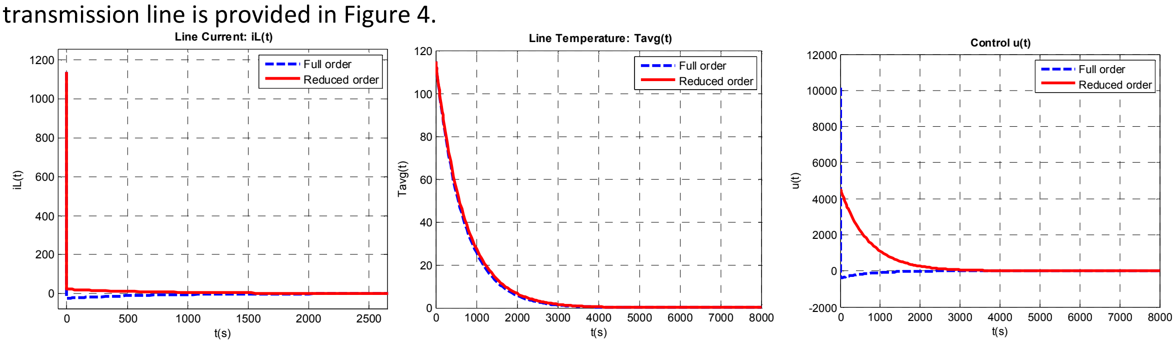

Figure 4. *States and control of linear transmission line model*

It was observed that the controller regulates the states to zero, for both full order and reduced order cases. The very close matching between the full order and reduced order LQR control manifests the effectiveness of the time scale method. Thus the proposed method provides almost the very same control action with less computational effort. This implies that lower order controllers could be implemented online for applications that demand real-time monitoring and control.

5.2 Stability of Transmission Line with Two Controllers

The results of simulation for the three cases of control inputs mentioned in Section 4.2 are given in Figure 5.

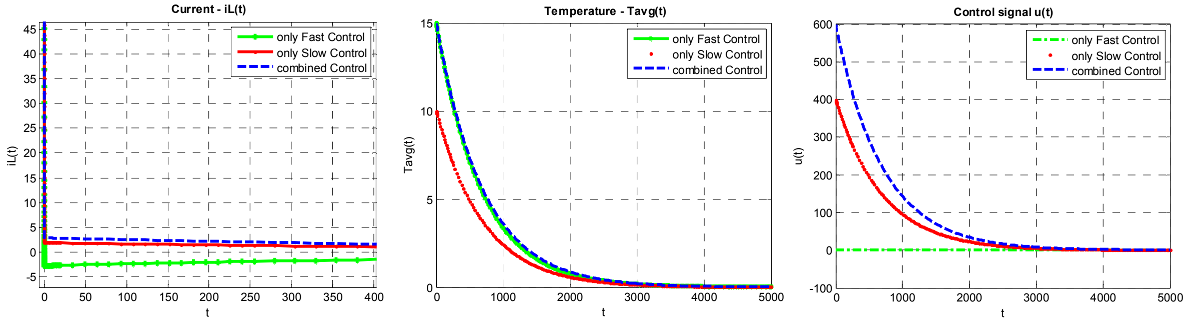

Figure 5. *Comparison of state responses to single control input and combined control input*

The last plot shows the 3 cases of control inputs. The 1st two plots display the response of current and temperature states to the three control inputs. It is observed that the states' response to the single control input (either slow or fast) is very close to that of the combined control input. This shows that even in the absence/failure of one of the controllers, the remaining control effort does provide comparable control to the whole system. This reiterates the strength of the time-scale control design approach, which provides (multiple controllers) resiliency to the systems as compared to a centralized control design.

Conclusions

A time domain modelling approach was presented to capture the electrical and thermal dynamics of transmission lines. This model renders instantaneous values of line current and line temperature, which are very useful information for Dynamic Line Rating of transmission lines. These instantaneous values when fed to an operator or a decision making controller, would help establish the safe line ampacity levels based on real-time conductor temperature.

Time scale techniques were presented that facilitated simpler controller designs to mitigate system perturbations. The simulation results confirm that comparable control action can be delivered with separate lower order slow and fast controllers. In a real scenario where various components of a power system chain are modelled (typically comprising of generators, transmission lines, power electronic interface dynamics, etc.), the combined model order could be very high, and controller design/online implementation, becomes computationally challenging. With the proposed time scale approach, higher order systems could be reduced to lower order subsystems, based on the number of time scales present in the entire system. Lower order models offer significant computational savings, and facilitate online control implementations. Finally, it was demonstrated that the presence of multiple controllers in place of one central controller guarantees comparable control action during failure of one of the controllers in the system, thereby ensuring resiliency and stability of the transmission system.

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