Abstract—The paper deals with design of power converters for optimal disturbance rejection. Both circuit parameters and control input are optimized simultaneously in a joint procedure. In general, the optimization problem requires solving bilinear matrix inequalities. For the buck converter, we show that the original problem can be reformulated equivalently as two simpler min-max problems that are solved successively. As a result, the optimal circuit parameters which minimize the impact of the disturbance are found. The circuit parameters and control are verified in simulation.

I. INTRODUCTION

In the design of a power converter, the two main objectives are often to minimize the power losses and to maximize the dynamic performance. These objectives must be optimized subject to constraints on quantities such as converter cost, volume or mass. Conventionally, the design procedure is split into two consecutive stages. In the first stage, the circuit parameters are selected in order to optimize the losses and to respect the design constraints [1]. In the second stage, the controller is designed based on fixed circuit parameters to optimize the dynamic performance. This two-stage approach implicitly assumes that the minimization of the losses and the maximization of the dynamic performance are independent and can be considered separately. Indeed, some of the system characteristics such as the ripple and the losses mostly depend on circuit parameters and only in a very minor way on the controller design. On its side, the controller significantly affects low frequency harmonics (distortion below the switching frequency) through its tracking capability and rejection of disturbances, which characterize its dynamic performance. It also affects the losses during transient. If these latter losses are significant, they can also be optimized, which requires a trade-off between the losses and the dynamic performance. The system dynamic performance that is optimized in the second stage does however not only depend on the controller design, but also on the circuit parameters that were fixed in the first design stage. The circuit parameters are usually not readjusted afterward. A better dynamic performance could however generally be obtained if the circuit parameters were also selected according to the desired dynamic performance during the circuit design stage.

A better overall performance could therefore be obtained by jointly designing the circuit parameters and the controller in a single optimization procedure. Several early research works have investigated the joint design of plant and controller parameters [2], [3]. Recently, most of the activity has been concentrated on applications in the area of mechatronics, where this simultaneous design procedure is called integrated structure and controller design or simply integrated design [4]–[12]. The biggest difficulty related to integrated design is probably that the resulting optimization problem is non convex. This problem can be tackled directly using nonlinear programming or it can be formulated in some cases as a simpler problem by using adequately the problem structure. Sequential quadratic programming is often used to solve the nonlinear problem directly [7], [10]. This often results in time consuming computations and bad convergence. In [8] a 3-stage approach is proposed where the problem is posed as a set of \( n \) closed-loop specifications to be satisfied. A solution is found for each of these specifications. In a second stage, a linear combination of these solutions that satisfy all specifications is sought. The solution is either non-existing or not unique. In the latter case, the sought solution is improved in a third stage by adding an additional optimization criterion to the problem. This approach is suitable when sensible specifications are available and when the objective is to find a solution to a set of specifications. It is not suitable if the problem is to find the optimal solution.

In the area of power electronics, only a few similar research works have followed the integrated approach. In [13], the integrated design and control of a buck converter is investigated. The paper presents the optimization of the dynamic performance, resulting in a linear state feedback controller synthesized based on covariance control theory. More recently, [14] has investigated how to maximize the dynamic performance of a buck-boost converter using an integrated design approach. As the considered buck-boost converter has nonlinear dynamics, a linearized averaged model is considered to simplify the problem. The synthesis of a PID is considered. The parameters of this linear model, the circuit and the controller parameters to be optimized, are factors of the state variables, resulting in a nonlinear optimization problem. Several operating conditions representative of the converter operation are taken as reference to measure the converter performance using a quadratic cost. These reference trajectories are combined in the same cost function to be optimized. Sequential quadratic programming is then used to solve the resulting nonlinear optimization problem.

The approaches that deal with integrated design all rely on a predefined linear controller structure (PID, H\(_\infty\), etc.), sometimes of a variable order. They provide the optimal parameters for these predefined controller structures, but...
they do not in general provide the optimal controller. One reason is that these control approaches cannot deal with the actuator limitations that are most of the time predominant in switched systems. The solution they sometime adopt to avoid nonlinearities caused by the actuator limitation consists in adding constraints to the optimization problem to obtain controller and structure parameters such that no saturation is activated during the controller normal operation. The optimal control action during abrupt transient however often consists in saturating the actuator for a while to give the fastest possible response. It is however not possible to obtain such control action with a linear controller. The other reason that prevents from finding out the optimal controller is the necessity to try iteratively all possible controller structures to find the optimal one.

Recent research works dealing only with the control have investigated the minimum time response of DC-DC power converters to disturbances [15]–[17]. These control solutions have been tailored to approach the dynamic performance limits of the power stages of switched mode power supplies. They however rely on known circuit parameters and their structures make them inappropriate for a joint optimization procedure.

The present project aims at filling the gap between the methods that optimally design the circuit parameters with a non-optimal controller and the optimal control methods. The focus is on switched power electronics systems. The objective is to optimally design the circuit parameters for control methods that give a performance close to the limits of the circuit. The considered design objectives are dynamic performance and energy efficiency (or equivalently the losses). Additional design constraints that limit volume, mass and costs are also considered.

The outline of the paper is as follows. In Section II we state the problem we ideally want to solve. In Section III we derive a system model and introduce parametrization which makes the problem tractable. In Section IV we solve the optimization problem in a two-stage approach and in Section VI the controller and circuit parameters obtained are verified in simulation. Finally, in Section VII we draw conclusions.

II. PROBLEM STATEMENT

A. Continuous-time model

We consider the dynamics of the buck converter shown in Fig. 1. This system comprises one switch. The position of the switch is described by the function \( s(t) \), which takes values 0 or 1 only. The system dynamics are therefore hybrid discrete and continuous. Defining the state as \( \mathbf{x} := [v_c \quad i_c]^T \) where \( v_c \) is the capacitor voltage and \( i_c \) is the inductor current, the system dynamics are described by

\[
\begin{align*}
\dot{x}(t) &= A_c x(t) + s(t) B_c v_s(t) + B_{w,c} i_{load}(t) \\
y(t) &= C x(t)
\end{align*}
\]

where \( A_c = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{L} & 0 \end{bmatrix}, \ B_c = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}, \ B_{w,c} = \begin{bmatrix} -\frac{1}{C} \\ 0 \end{bmatrix} \). In the system (1), the switch signal \( s(t) \) is the control variable. The source voltage \( v_s \) and load current \( i_{load} \) are disturbance signals. The losses have been neglected in this model to simplify its structure.

B. Control and design objectives

The main control objective is to keep the output \( y := v_c \) at the given reference level \( y_{ref} \) and to minimize the effect of the variations of \( v_s \) and \( i_{load} \) on the output.

From the point of view of the system design, we seek both for the circuit parameters and the controller that suit best this objective. We need to optimize the converter capacitor \( C \), its inductance \( L \), the sampling time \( T_s \) and the manipulated variable \( s(t) \), using a discrete time controller for a range of supply voltages \( v_s \) and load currents \( i_{load} \).

The control problem considered is optimal disturbance rejection. We consider the evolution of the system state over a finite time window of length \( T_f \) and seek to minimize the impact of the worst case disturbance. If the source voltage and load current are considered as disturbances, the problem can be formally stated as

\[
\begin{align*}
\min_{s,L,C,T_s} \max_{v_s,i_{load}} \int_0^{T_f} J(x, s, L, C, T_s) \, dt
\end{align*}
\]

for some suitable cost function \( J \). The optimization is subject to constraints on the optimization variables. It should be noted that the minimization is not only over the control input \( s(t) \), but also over the circuit parameters \( L, C, T_s \).

Even if the plant has linear dynamics, the simplest joint optimization problem is bilinear with respect to the optimization variables. Indeed, even in the simplest case where the circuit parameters to be optimized appear as simple factors in the discrete time model, these factors multiply the states and inputs in the optimization problem. To be solved using brute force, the simplest problem involves nonlinear programming, which makes the problem relatively difficult especially for large dimension systems. We propose here to exploit the structure of the power converter dynamics and some analysis of the system properties to solve the problem in a much simpler way.

III. OPTIMIZATION MODEL

A. Discrete time models

The hybrid equations (1) are modeled in discrete time by using the matrix exponential and a zero order hold model for the control input and disturbance. This model is commonly

\[
\begin{align*}
\dot{x}(t) &= A_c x(t) + s(t) B_c v_s(t) + B_{w,c} i_{load}(t) \\
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where \( A_c = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{L} & 0 \end{bmatrix}, \ B_c = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}, \ B_{w,c} = \begin{bmatrix} -\frac{1}{C} \\ 0 \end{bmatrix} \). In the system (1), the switch signal \( s(t) \) is the control variable. The source voltage \( v_s \) and load current \( i_{load} \) are disturbance signals. The losses have been neglected in this model to simplify its structure.

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III. OPTIMIZATION MODEL

A. Discrete time models

The hybrid equations (1) are modeled in discrete time by using the matrix exponential and a zero order hold model for the control input and disturbance. This model is commonly
used for numerical analysis as it gives an accurate approximation $x_k$ of the state $x(kT_s)$ at the switching instances. The model is

$$x_{k+1} = Ax_k + d_k B v_{s,k} + B w_{i_{load,k}},$$

$$0 \leq d_k \leq 1$$

(2)

where $d_k$ is the $k$th duty cycle, $v_{s,k}$ and $i_{load,k}$ are the voltage source and load current at time $kT_s$ and where

$$A = e^{A_s T_s} = \left[ \begin{array}{cc} \cos \omega_r T_s & \frac{1}{\omega_r} \sin \omega_r T_s \\ -\frac{1}{\omega_r} \sin \omega_r T_s & \cos \omega_r T_s \end{array} \right]$$

$$B = \left[ \begin{array}{c} 0 \\ \frac{T_s}{L} \end{array} \right], \quad B_w = \left[ \begin{array}{c} -\frac{T_s}{L} \\ 0 \end{array} \right], \quad \omega_r = \frac{1}{\sqrt{LC}}.$$ 

In (2), the circuit parameters to be optimized appear in transcendental functions of the resonance frequency $\omega_r$, which is not suitable for our optimization procedure. A model more suitable for parameter extraction can be obtained by using forward Euler approximation on (2). Thus we obtain the system

$$x_{k+1} = \left[ \begin{array}{c} \frac{T_s}{L} \\ 1 \end{array} \right] x_k + d_k \left[ \begin{array}{c} 0 \\ \frac{T_s}{L} \end{array} \right] v_{s,k} + \left[ \begin{array}{c} -\frac{T_s}{L} \\ 0 \end{array} \right] i_{load,k},$$

$$0 \leq d_k \leq 1$$

(3)

In the model (3), $1/C$ and $1/L$ appear as simple factors, which is more suitable for our optimization.

**B. Model reformulation**

Consider the discrete time model (3). The effect of the switching $s(t)$ is hidden in the duty cycle $d_k$ as the model was averaged from the initial switched system. The design parameters $T_s$, $C$ and $L$ cannot be separated from the two model ratios $T_s/C$ and $T_s/L$. Moreover, from the last row of the dynamic equations it is clear all the pairs $(\frac{T_s}{L}, d_k)$ that yields the same value

$$f \left( \frac{T_s}{L}, d_k \right) = T_s \left( d_k v_{s,k} - v_{c,k} \right) \quad 0 < d_k < 1 \quad (4a)$$

have the same effect (on the discrete time model). Thus, the ratio $\frac{T_s}{L}$ and the duty cycle $d_k$ cannot be separated without adding further constraints to the problem. We collect the quantities in (4) in a new variable $p_1 \cdot u_k$ where

$$p_1 := \frac{T_s}{L}, \quad u_k := d_k v_{s,k} - v_{c,k}$$

and use $p_1 u_k$ as new control input. We keep $p_1$ as explicit factor in this control input for convenience for later discussion. The control input that produces a given effect on the system is now unique. The discrete time model (3) becomes

$$x_{k+1} = \left[ \begin{array}{c} \frac{T_s}{L} \\ 1 \end{array} \right] x_k + \left[ \begin{array}{c} 0 \\ 1 \end{array} \right] p_1 u_k + \left[ \begin{array}{c} -\frac{T_s}{L} \\ 0 \end{array} \right] i_{load,k},$$

$$T_s \left( -v_{c,\text{max}} \right) \leq p_1 u_k \leq T_s \left( v_{s,\text{max}} - v_{c,\text{min}} \right)$$

(5)

where $v_{s,\text{min}}, v_{s,\text{max}}, v_{c,\text{min}}, v_{c,\text{max}}, L_{\text{min}}$ and $L_{\text{max}}$ are the lower and upper boundaries of $v_{s,k}, v_{c,k}$ and $L$ respectively. The ratio $\frac{T_s}{L}$ still appears in the dynamics as variable to optimize. We can further substitute $i_{f,k}, u_k, i_{\text{load,k}}$ with new variables

$$i_{f,k} := \frac{T_s}{C} i_{f,k}$$

(6a)

$$p_2 := \frac{T_s}{C}$$

(6b)

$$w_k := -i_{\text{load,k}}$$

(6c)

$$\mathbf{x} := \left[ \begin{array}{c} y_k := v_{c,k} \\ i_{f,k} \end{array} \right]$$

(6d)

in order to remove the remaining ambiguity. Using these substitutions, the only variable that keeps its original physical meaning is the control output $y$. This is a mandatory condition to be able to formulate our problem. The final discrete time model becomes

$$x_{k+1} = \left[ \begin{array}{cc} 1 & 1 \\ 0 & 1 \end{array} \right] x_k + \left[ \begin{array}{c} 0 \\ 1 \end{array} \right] u_k' + \left[ \begin{array}{c} 1 \\ 0 \end{array} \right] p_2 w_k$$

(7a)

$$u_k' := p_1 p_2 u_k$$

(7b)

$p_1$ and $p_2$ are strictly positive factors. $p_2$ directly modulates the effect of the disturbance on the control output and the effect of the control input on the system. A small factor $p_2$ therefore reduces the impact of a disturbance on the system. It also reduces the effect of the control input on the system but this can be compensated by a large $p_1$.

**IV. PROBLEM FORMULATION AND SOLUTION**

The outcome of the previous section is a linear model of the optimization variables. In this section, we decompose the optimization problem into two sub-problems, which are min max problems. In the first optimization sub-problem we look at the worse case load current, the effect of the supply voltage being embedded in an auxiliary input. In the second optimization sub-problem, we look at the worse case supply voltage by decoupling it from the optimal auxiliary control input sequence obtained from the first min-max problem.

**A. First optimization sub-problem**

**1) Min-max formulation:** We formulate the following finite horizon optimal min-max control problem:

$$\min_{u_{c,p_2 y_{ref},w_0}} \max_{\mathbf{x}_N} \sum_{n=1}^{N} (y_{ref} - C x_n)^T Q (y_{ref} - C y x_n)$$

(8a)

subject to the model (7) and to the constraints

- initial steady state operating point $x_0 = \left[ \begin{array}{c} y_{ref} \\ w_0 \end{array} \right]$
- load disturbance set $w_{\text{min}} \leq w_n \leq w_{\text{max}}$
- load does only one step $w_{n+1} = w_n \forall n \geq 1$
- parameter feasible sets $p_{2,\text{min}} \leq p_2 \leq p_{2,\text{max}}$
- $p_{1,\text{min}} \cdot p_{2,\text{min}} \cdot u_{\text{min}} \leq u_k' \leq p_{1,\text{max}} \cdot p_{2,\text{max}} \cdot u_{\text{max}}$

(8d)

(8e)

(8f)

The maximum of a convex function over a convex set is attained at an extreme point of the set [18]. Since the disturbance belongs to a convex set $W$, we can solve the min-max problem (8) by enumerating the disturbance sequence.
\( w_n \) \( V \) over the vertices of \( V \). For a fixed sequence \( V \) the min-max problem reduces to a convex QP which can be solved efficiently. The reference \( y_{\text{ref}} \) is often constant in practice, which reduces the number of iterations. In the present case, we want to investigate how fast an abrupt disturbance can be compensated. Starting from any steady state operating point, we seek for the best response. We do not consider the case when the disturbance has some dynamics, we instead consider the case when it varies by (distant) steps, such that we can consider that it can only change once at the beginning of the prediction horizon, which further reduces the number of iterations.

2) Result interpretation: Solving the problem (8), we obtain the optimal circuit parameter \( p_1^* \), the optimal sequence of input, \( U^* = \{ u_0^*, u_1^*, \ldots, u_{N-1}^* \} \), the associated sequence of optimal states \( X^* = \{ x_1^*, x_2^*, \ldots, x_N^* \} \), the worst sequence of disturbance \( W^* = \{ w_1^*, w_2^*, \ldots, w_N^* \} \) and the worse reference \( y_{\text{ref}}^* \). The only result than can directly be interpreted is \( p_2 \), which allows to deduce the capacitance value \( C \) for a given sampling time \( T_s \). In that case, the optimal capacitance is \( C_{\text{max}} \) as expected.

B. Second optimization sub-problem

We have not yet obtained the optimal value \( p_1^* \) which is coupled with \( u_k^* \). We can link the sequence of optimal input with the sequence of optimal states using (4a) and (7b). Rewriting the constraint on the duty cycle from (3), we can then define the solution of (8) as the set satisfying the following constraints:

\[
\begin{align*}
  u_0^* &= p_1 \cdot p_2^* \cdot (d_0 \cdot v_{s,0} - v_{c,1}) \quad 0 < d_0 < 1 \\
  u_1^* &= p_1 \cdot p_2^* \cdot (d_1 \cdot v_{s,1} - v_{c,2}) \quad 0 < d_1 < 1 \\
  &\vdots \\
  u_{N-1}^* &= p_1 \cdot p_2^* \cdot (d_{N-1} \cdot v_{s,N-1} - v_{c,N}) \quad 0 < d_{N-1} < 1
\end{align*}
\]

(9)

1) Min-max problem formulation: In order to minimize the ripple (which is not predicted by our discrete time model), we additionally want to maximize the size of the inductance or we can equivalently find the smallest \( p_1 \) that satisfies (9). This value will satisfy optimum disturbance rejection and minimal ripple as secondary objective. As \( p_1 \) and \( v_{s,k} \) are strictly positive, we rewrite conveniently our equalities and inequalities. Introducing the auxiliary variables \( v_k = d_k \cdot v_{s,k} \) and \( p_3 = 1/p_1 \), (9) is equivalently stated

\[
\begin{align*}
  u_0^* \cdot p_3 &= p_2^* \cdot (v_0 - v_{c,1}) \quad 0 < v_0 < v_{s,0} \\
  u_1^* \cdot p_3 &= p_2^* \cdot (v_1 - v_{c,2}) \quad 0 < v_1 < v_{s,1} \\
  &\vdots \\
  u_{N-1}^* \cdot p_3 &= p_2^* \cdot (v_{N-1} - v_{c,N}) \quad 0 < v_{N-1} < v_{s,N-1}
\end{align*}
\]

(10)

We can now formulate the following min-max problem:

\[
\min_{v_{s,n}, p_3} \max_{v_{s,n}} \sum_{n=1}^{N} p_3^2 
\]

subject to the constraints (10) and

\[
\frac{L_{\text{min}}}{T_{s,\text{max}}} \leq p_3 \leq \frac{L_{\text{max}}}{T_{s,\text{min}}} \quad (11b)
\]

\[
v_{s,\text{min}} \leq v_{s,k} \leq v_{s,\text{max}} \quad (11c)
\]

We now seek for the biggest \( p_3 \), which is solution of (8) and which therefore minimizes the impact of all disturbances on the system. We apply the same iterative procedure as in (8) to solve the problem.

2) Result interpretation: We have obtained the optimal circuit parameter \( p_1^* = 1/p_1^* \), the optimal sequence of control inputs \( V^* = \{ v_0^*, v_1^*, \ldots, v_{N-1}^* \} \), the worst sequence of supply voltages \( V_s^* = \{ v_{s,0}, v_{s,1}, \ldots, v_{s,N-1}^* \} \).

C. Summary

We have obtained the optimal ratios

\[
\begin{align*}
  p_1^* &= \frac{T_s^*}{L^*} \quad (12a) \\
  p_2^* &= \frac{T_s^*}{C^*} \quad (12b)
\end{align*}
\]

that define the optimal circuit parameters that allow the maximum achievable dynamic performance with respect to the disturbance for this converter structure. An infinite number of parameters \( p_1 \) permit to achieve the same performance. Solving (11), we have selected the biggest in order to minimize the ripple. Solving (8), \( p_2 \) has no minimum if no constraint is added to the problem, we therefore obtain \( p_2^* = p_2,_{\text{min}} \). \( p_2^* = p_2,_{\text{min}} \) could also be obtained solving another similar problem specifying the converter start-up time.

V. NUMERICAL APPLICATION

Our example application is specified as follow:

\[
\begin{align*}
  7V &< v_s < 30V \\
  0A &< i_{\text{load}} < 0.5A \\
  v_{\text{ref}} &= 5V
\end{align*}
\]

As we want results that we can directly interpret for our example, we specify the sampling and switching periods:

\[
T_s = 10\mu s
\]

We specify the admissible capacitor and inductance ranges:

\[
\begin{align*}
  0.1\mu F &< C < 100\mu F \\
  1\mu H &< L < 10mH
\end{align*}
\]

We fix the sampling frequency as it is undetermined in the present formulation. Solving the first min-max problem that was formulated in (11) we obtain the optimal auxiliary input, output and load current shown in Fig. 2. We also obtain the optimal ratio \( T_s^* \). As we fixed the sampling period, we can directly extract the optimal capacitor value \( C^* = 100\mu F \).

As expected with this disturbance rejection formulation, the optimal capacitor is the biggest we allowed. These variables depend only on the boundaries of the reference \( v_{\text{ref}} \) and
the load current $i_{\text{load}}$. $y$ and $w$ correspond to the optimal capacitor voltage and to the worse disturbance, while the optimal input cannot be directly interpreted.

An interesting property than we can deduce from these results is that the voltage deviation does not depend on the switching frequency. A disturbance is always compensated in the same number of sampling times and the maximum deviation does not depend on the sampling period. Fig. 2 features this optimal response.

We use these results to solve the second min-max problem (see (8)) in order to obtain the optimal ratio $\frac{L}{L}$ and the optimal inductance $L^* = 50\mu\text{H}$. We also obtain the real control input, that we do not use as it is only a intermediate result to obtain the optimal circuit parameters.

VI. SIMULATION RESULTS

In this section, we verify the results obtained in the previous system by simulating the real system using the optimal parameters obtained in $V$.

To this end, we evaluate the disturbance rejection obtained for a buck converter with optimal circuit parameters. The optimal control law, the explicit model predictive controller described in [19] is used to optimally control this power converter. A worse case test is featured in Fig. 3. A start-up is followed by a step in the load current for the smallest supply voltage we obtained solving the min-max problem ($v_s = 7\text{ V}$). The maximum load step is applied. The measured deviation is a bit more important than featured in Fig. 2 (from optimization model) especially during the second load step. The two reasons are that we neglected the fact that there is a time delay between the measurements and the actuation. This delay was neglected for simplicity but it could however be taken into account in the parameter optimization. The second reason explaining the mismatch is that the simulated scheme features observers that compensate the delay (and thus allows stability of the closed-loop system) but that also filter the detection of disturbances.

To verify that our design is correct, we repeat the same simulation with non optimal parameters (twice the inductance, half the capacitor). In Fig. 4, we can see that the deviation from the reference is significantly higher, which confirms the approach effectiveness.

It has to be noted that the performance obtained in circuit parameters optimization procedure is an upper limit that can only be achieved on the approximate linear average model. This performance might not be achievable on the real system due to phenomena such as the switching.

VII. CONCLUSIONS

We have proposed to solve the simultaneous optimization of the circuit parameters and control input using a variable
substitution technique and a decomposition of the general min-max problem into two simpler min-max problems. Instead of solving a nonlinear program, we can solve each min-max problem more efficiently solving several QP. The first min-max problem yield the optimal sequence of state for the worst case load, which is unique, one of the sought circuit parameter and an auxiliary control input which embeds the effect of the other disturbances. These results are used in a second min-max problem to obtain the real optimal control input and the remaining circuit parameter.

From this investigation it follows that the optimal output response is independent of the sampling period, as a consequence the optimal ratios are valid for any switching frequency. Moreover the capacitance is limited only by constraints limiting the volume, cost and start-up time. Based on the discrete-time model, we found that an infinite number of inductance satisfy optimal disturbance rejection. Adding a secondary objective to minimize the ripple, the solution is unique.

Simulations of the real system confirm the results.

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