**Stabilization of Stochastic Differential Equations Driven by G-Brownian Motion with Aperiodically Intermittent Control**

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**Abstract:** The paper is devoted to studying the exponential stability of a mild solution of stochastic differential equations driven by G-Brownian motion with an aperiodically intermittent control. The aperiodically intermittent control is added into the drift coefficients, when intermittent intervals and coefficients satisfy suitable conditions; by use of the G-Lyapunov function, the $p$-th exponential stability is obtained. Finally, an example is given to illustrate the availability of the obtained results.

**Keywords:** exponential stability; aperiodically intermittent control; G-Brownian motion; stochastic differential equations

1. Introduction

In this paper, stochastic differential equations driven by G-Brownian motion (G-SDEs) are considered as follows

\[ dx(t) = f(t, x(t))dt + g(t, x(t))d\langle B\rangle(t) + \sigma(t, x(t))dB(t), \quad t \geq 0, \]

where the coefficients $f, g, \sigma : \mathbb{R}^+ \times \mathbb{R}^n \to \mathbb{R}^n$, $x(0) = x_0 \in \mathbb{R}^n$. $B(t)$ is G-Brownian motion, $\langle B \rangle(t)$ is usually called the quadratic variation process of G-Brownian motion. Due to the nonlinear properties of expectation with G-Brownian motion, G-SDEs are more general than classical SDEs driven by Brownian motion, and can be widely used in many fields. With the development of G-theory and related stochastic calculus ([1]), many interesting results of G-SDEs have been obtained, for instance, existence, uniqueness, boundedness ([2–7] and the references therein).

As we know, stability is one of the most interesting topics in dynamic behaviors. Regarding SDEs, many interesting works have been obtained on this issue (one can see [8,9]). Similarly, a lot of researchers have made great efforts on the subject of G-SDEs, for instance, exponential stabilization and quasi-sure exponential stabilization ([10]). However, the most relevant is how to make an unstable system stable. Recently, an aperiodically intermittent control has been presented to make systems stable ([11,12]). In particular, Yang et al. [13] investigated the stability of a solution of G-SDEs by constructing an aperiodically intermittent control which is set in diffusion coefficient. Meanwhile, based on the stability of G-SDEs, the stabilization of a stochastic Cohen–Grossberg neural networks driven by G-Brownian motion was established. A natural problem is whether one can stabilize the G-SDEs when an aperiodically intermittent control is added into the drift coefficients. As far as we know, there is no result on this topic. Taking the issue under consideration, we will investigate the stability of (1) with an aperiodically intermittent control added into the drift coefficient

\[ dy(t) = f(t, y(t))dt + h(s)g(t, y(t))d\langle B\rangle(t) + h(s)\sigma(t, y(t))dB(t), \quad t \geq 0, \]
where the aperiodically intermittent control

\[ h(t) = \begin{cases} -1, & t \in [t_i, s_i) \\ 0, & t \in [s_i, t_{i+1}) \end{cases} \]

\( t_{i+1} - s_i \) is the rest width and \( s_i - t_i \) is the control width. Let \( \inf_i (s_i - t_i) = \mu > 0 \), \( \sup_i (t_{i+1} - t_i) = \nu < \infty \), \( \psi_k = (t_{k+1} - s_k)(t_{k+1} - t_k)^{-1} \) and \( \psi = \limsup_{k \to \infty} \psi_k > 0 \).

Differing from Yang et al. [13], we investigate the stabilization problem of G-SDEs, whose drift coefficients are added with an aperiodically intermittent control. The main innovations and contributions of this paper are highlighted as follows.

- A new aperiodically intermittent control is designed to stabilize this class stochastic system, driven by G-Brownian motion. Moreover, the aperiodically intermittent control is added to the drift coefficient.
- The aperiodically intermittent interval satisfies

\[ a_2 \psi < a_1 (1 - \psi), \]

where \( \psi_k = (t_{k+1} - s_k)(t_{k+1} - t_k)^{-1} \) and \( \psi = \limsup_{k \to \infty} \psi_k > 0 \), which can be easily realized.
- By the Lyapunov function satisfying suitable conditions, the \( p \)-th exponential stability is obtained. When \( p = 2 \), it is the exponential stability in mean square. Finally, an example is presented to show the efficiency of the obtained result.

The rest of the paper is arranged as follows. In the next section, some basic notions, preliminaries and lemmas are provided. In Section 3, we prove exponential stability for the solution of G-SDEs, whose drift coefficients are added to an aperiodically intermittent control. Finally, an example is presented to show the efficiency of the result.

2. Notations

In this section, some notations, with respect to G-Brownian motion and related stochastic calculus, are introduced. \( \Omega \) denotes the collection of all continuous functions \( \omega \) on \( \mathbb{R}^n \) with \( \omega_0 = 0 \), and the distance in \( \Omega \) is given by

\[ \rho(\omega^1, \omega^2) = \sum_{i=1}^{\infty} 2^{-i} \left[ \max_{i \in [0, d]} |\omega^1_i - \omega^2_i| \right] \land 1. \]

\( B_t(\omega) \) is the canonical process and is defined by \( B_t(\omega) = \omega_t, \ t \geq 0 \). The filtration \( \mathcal{F}_t \) generated by \( (B_t)_{t \geq 0} \) is given with \( \mathcal{F}_t = \sigma(B_s, 0 \leq s \leq t) \), and \( \mathcal{F} = \bigvee_{t \geq 0} \mathcal{F}_t, \mathbb{E} \) is a sublinear expectation defined on \( (\Omega, \mathcal{F}) \).

We denote \( C_{b,Lip}(\mathbb{R}^n) \) as the space of all bounded Lipschitz continuous functions on \( \mathbb{R}^n \), and

\[ \mathcal{L}_{Lip}(\mathcal{F}) = \left\{ \xi : \phi(B(t_1), B(t_2), \ldots, B(t_n)), n \geq 1, 0 < t_1 < t_2 < \cdots < t_n < \infty, \phi \in C_{b,Lip}(\mathbb{R}^n) \right\}. \]

Definition 1. A random variable \( X \) is G-normally distributed, denoted by \( X \sim N(0, [\sigma, \bar{\sigma}]) \), \( 0 \leq \bar{\sigma} \leq \sigma \), if for any \( \xi \in \mathcal{L}_{Lip}(\mathcal{F}) \), the operator defined by \( \mathbb{E} \left[ \xi \left( x + \sqrt{t}X \right) \right] := u(t, x) \) is the viscosity solution of the following nonlinear heat equation

\[ \begin{cases} \frac{\partial u}{\partial t} - G \left( \frac{\partial^2 u}{\partial x^2} \right) = 0 \\ u(0, x) = \xi(x), \end{cases} \]
where \( G(r) = \frac{1}{2}(\sigma^2 r^+ - \sigma^2 r^-), r \in \mathbb{R} \).

**Definition 2.** The canonical process \( B(t)_{t \geq 0} \) is called G-Brownian motion, if the following properties are verified

1. \( B_0(\omega) = 0; \)
2. For each \( t, s \geq 0 \), the increment \( B(t + s) - B(s) \sim N(0, [\sqrt{\bar{\sigma}}^+, \sqrt{\bar{\sigma}}^-]) \) and is independent from \( B(t_1), B(t_2), \cdots, B(t_n) \), for any \( 0 \leq t_1 \leq t_2 \leq \cdots \leq t_n \).

Furthermore, the sublinear expectation \( \mathbb{E} \) is called the G-expectation.

In the following part, we introduce the Itô integral with respect to the G-Brownian motion. Firstly, some space notations are presented.

\( L^p_G(\mathcal{F}_T)(p \geq 1) \) is the completion of \( L_{lip}(\mathcal{F}_T) \) with the norm \( \|X\| = \left\{ \mathbb{E}\|X\|^p \right\}^{\frac{1}{p}}, \) as well as, \( L^p_G(\mathcal{F}) \) is considered as the completion of \( L_{lip}(\mathcal{F}) \). Furthermore

\[
\mathcal{M}^p_G([0,T]) = \left\{ g_t = \sum_{j=1}^{N} \xi_{t_j} I_{[t_j,t_{j+1})}(t); \xi_{t_j} \in L^p_G(\mathcal{F}_j), t_{j-1} < t_j, j = 1, 2, \ldots, N \right\}.
\]

\( \mathcal{M}^p_G([0,T]) \) is denoted as the completion of \( \mathcal{M}^p_G([0,T]) \) satisfying

\[
\|S\|_{\mathcal{M}^p_G([0,T])} = \left( \int_0^T \mathbb{E}\|S\|^p \right)^{\frac{1}{p}}.
\]

**Definition 3.** (Itô Integral) For \( g_t = \sum_{j=0}^{N-1} \xi_{t_j} I_{[t_j,t_{j+1})} \in \mathcal{M}^p_G([0,T]), \) Itô integral with respect to \( B(t) \) is defined

\[
\int_0^T g_t dB(s) := \sum_{j=0}^{N-1} \xi_{t_j} (B(t_{j+1}) - B(t_j)),
\]

moreover, the quadratic variation process of the G-Brownian motion \( B(t) \) is defined by

\[
\langle B \rangle_t := \lim_{N \to \infty} \sum_{j=0}^{N-1} \left( B^N(t_{j+1}) - B^N(t_j) \right)^2 = B^2(t) - 2 \int_0^t B(s) dB(s).
\]

**Definition 4.** For any \( g_t \in \mathcal{M}^1_G([0,T]), \) define

\[
\int_0^T g_t dB(t) := \sum_{j=0}^{N-1} \xi_{t_j} [\langle B \rangle(t_{j+1}) - \langle B \rangle(t_j)].
\]

3. **Main Results**

**Definition 5.** Suppose there exist positive constants \( \lambda \) and \( C \), such that the solution \( X(t) \) of (1) satisfies

\[
\mathbb{E}\|X(t)\|^p \leq C \mathbb{E}\|X(0)\|^p e^{-\lambda t}, \text{ for any initial value } X(0), p \geq 2,
\]

then, the mild solution \( X(t) \) is said to be \( p \)-th exponentially stable.

If \( V(t,x) \in C^{1,2}(\mathbb{R}^+ \times \mathbb{R}^n; \mathbb{R}^n) \), the Lyapunov operator \( L : \mathbb{R}^+ \times \mathbb{R}^n \to \mathbb{R}^n \) associated to the G-SDEs (1) is defined as below

\[
LV(t,x) = V_t(t,x) + V_x(t,x)f(t,x) + G((V_x(t,x), 2g(t,x)) + \langle V_{xx}(t,x)\sigma(t,x), \sigma(t,x) \rangle),
\]

where \( G(r) = \frac{1}{2}(\sigma^2 r^+ - \sigma^2 r^-), r \in \mathbb{R} \).
where
\[ V_i(t, x) = \frac{\partial V(t, x)}{\partial t}, \quad V_x(t, x) = \left( \frac{\partial V(t, x)}{\partial x_1}, \frac{\partial V(t, x)}{\partial x_2}, \ldots, \frac{\partial V(t, x)}{\partial x_n} \right), \]
\[ V_{xx}(t, x) = \left( \frac{\partial^2 V(t, x)}{\partial x_i \partial x_j} \right)_{n \times n}. \]

**Theorem 1.** Assume that the function \( V(t, x) \) associated with (2) is in \( C^{1,2}(\mathbb{R}^+ \times \mathbb{R}^n; \mathbb{R}^n) \) and there exist positive constants \( c_1, c_2, a_1, a_2, \gamma, M \) such that
\[ c_1 |y(t)|^p \leq V(t, y(t)) \leq c_1 |y(t)|^p, \quad \tag{3} \]
\[ L \leq V(t, y(t)) \leq -a_1 V(y(t)), \quad t \in [t_i, t_{i+1}), \quad \tag{4} \]
and
\[ L \leq V(t, y(t)) \leq a_2 V(y(t)), \quad t \in [t_i, t_{i+1}). \quad \tag{5} \]
Furthermore, suppose the aperiodically intermittent interval satisfies the inequality \( a_2 \psi < a_1 (1 - \psi) \), then
\[ \mathbb{E}|y(t)|^p \leq M\mathbb{E}|y(0)|^p e^{-\gamma t}, \quad \gamma \in (0, a_1 (1 - \psi) - a_2 \psi). \]

**Proof of Theorem 1.** Taking Itô formula to \( e^{\alpha t}V(t, x) \), we have
\[ d\{e^{\alpha t}V(t, y(t))\} = e^{\alpha t} \{ a_1 V(t, y(t)) + V_i(t, y(t)) + V_y(t, y(t)) f(y(t)) \} dt \]
\[ + e^{\alpha t} \langle V_g(t, y(t)), h(s)g(y(t)) \rangle dB(t) \]
\[ + e^{\alpha t} \langle V_{gg}(t, y(t)), h(s)\sigma(y(t)) \rangle dB(t) \]
\[ + \frac{1}{2} e^{\alpha t} \langle V_{ggg}(t, y(t)), h(s)\sigma(y(t)) \rangle dB(t). \quad \tag{6} \]
If \( t \in [t_0, s_0) \), it follows from (6)
\[ e^{\alpha t}V(t, y(t)) = e^{\alpha t_0}V(t_0, y(t_0)) + \int_{t_0}^t e^{\alpha s} [a_1 V(s, y(s)) + L(s, y(s))] ds + M^t_{s_0} \]
\[ + \int_{t_0}^t e^{\alpha s} \langle V_g(s, y(s)), h(s)\sigma(y(s)) \rangle dB(s), \quad \tag{7} \]
where
\[ M^t_{s_0} = \int_{t_0}^t e^{\alpha s} \langle V_g(s, y(s)), h(s)g(y(s)) \rangle dB(s) \]
\[ + \frac{1}{2} \int_{t_0}^t e^{\alpha s} \langle V_{gg}(s, y(s)) h(s)\sigma(y(s)), h(s)\sigma(y(s)) \rangle ds \]
\[ - \int_{t_0}^t e^{\alpha s} G(\{ V_g(s, y(s)), 2h(s)g(y(s)) \} + \langle V_{gg}(s, y(s)), h(s)\sigma(y(s)) \rangle) ds. \]
Following (4) and (7), it deduces
\[ e^{\alpha t}V(t, y(t)) \leq e^{\alpha t_0}V(t_0, y(t_0)) + M^t_{s_0} + \int_{t_0}^t e^{\alpha s} \langle V_g(s, y(s)), h(s)\sigma(y(s)) \rangle dB(s). \quad \tag{8} \]
From [5], \( \mathbb{E}M_t \leq 0 \), and by using G-expectation on (8), it shows
\[ \mathbb{E}e^{\alpha t}V(t, y(t)) \leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)). \quad \tag{9} \]
When $t \in [s_0, t_1)$, as similar way, we can get
\begin{align*}
e^{\alpha t}V(t, y(t)) &= e^{\alpha s_0}V(s_0, y(s_0)) + \int_{s_0}^{t} e^{\alpha s} [V(s, y(s)) + LV(s, y(s))] \, ds + M_{t_0}^s + \\ &+ \int_{s_0}^{t} e^{\alpha s} (V(s, y(s)) - h(s)c(y(s))) \, dB(s).
\end{align*}
\hspace{1cm} (10)
Again, taking the expectation on both sides of (11), and from (5), then
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha s_0}V(s_0, y(s_0)) + (a_1 + a_2) \int_{s_0}^{t} e^{\alpha s} \mathbb{E}V(s, y(s)) \, ds.
\end{align*}
\hspace{1cm} (11)
By means of the Gronwall inequality, we can claim that
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha s_0}V(s_0, y(s_0)) e^{(a_1 + a_2)(t - s_0)} \leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2)(t - t_0)}.
\end{align*}
For $t \in [t_1, s_1)$, we have
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha t_1}V(t_1, y(t_1)) \leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2)(t_1 - t_0)},
\end{align*}
We consider the other case $t \in [s_1, t_2)$,
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha s_1}V(s_1, y(s_1)) e^{(a_1 + a_2)(t - s_1)} \leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2)(t_1 - t_0) + (a_1 + a_2)(t - t_1)}.
\end{align*}
Repeating the aforementioned procedure, we have
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2) \sum_{k=0}^{i-1} (t_{k+1} - s_k)} \, t \in [t_i, s_j),
\end{align*}
and
\begin{align*}
\mathbb{E}e^{\alpha t}V(t, y(t)) &\leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2) \sum_{k=0}^{i-1} (t_{k+1} - s_k) + (a_1 + a_2)(t - s_i)} \leq \mathbb{E}e^{\alpha t_0}V(t_0, y(t_0)) e^{(a_1 + a_2) \sum_{k=0}^{i-1} (t_{k+1} - s_k)} \, t \in [s_i, t_{i+1}).
\end{align*}
With regard to the definition of $\psi$, for $t \in [t_i, s_j)$
\begin{align*}
(a_1 + a_2) \sum_{k=0}^{i-1} (t_{k+1} - s_k) - a_1 t &= (a_1 + a_2) \sum_{k=0}^{i-1} \psi_k (t_{k+1} - t_k) - a_1 t \leq (a_1 + a_2) \psi t - a_1 t.
\end{align*}
Thus,
\begin{align*}
\mathbb{E}V(t, y(t)) &\leq \mathbb{E}V(t_0, y(t_0)) e^{((a_1 + a_2) \psi - a_1) t} \, t \in [t_i, s_j).
\end{align*}
\hspace{1cm} (12)
By the definition of $\psi$ and $v$, for $t \in [s_i, t_{i+1})$
\begin{align*}
(a_1 + a_2) \sum_{k=0}^{i} (t_{k+1} - s_k) - a_1 t &= (a_1 + a_2) \sum_{k=0}^{i} [\psi_k (t_{k+1} - t_k)] - a_1 t \leq (a_1 + a_2) \psi t + (a_1 + a_2) \psi (t_{k+1} - t) - a_1 t \leq [(a_1 + a_2) \psi - a_1] t + (a_1 + a_2) \psi v.
\end{align*}
Then,
\[ EV(t, y(t)) \leq EV(t_0, y(t_0))e^{(a_1 + a_2)\psi t}e^{(\psi - \beta_1)t}, \quad t \in [s_i, t_{i+1}). \quad (13) \]

From (12) and (13), we obtain
\[ EV(t, y(t)) \leq EV(t_0, y(t_0))e^{(a_1 + a_2)\psi t}e^{-\beta t}, \quad t \geq 0. \]

It follows from (3) that
\[ E|y(t)|^p \leq \frac{C_2}{c_1}E|y(0)|^p e^{(a_1 + a_2)\psi t}e^{-\beta t}, \quad t \geq 0. \]

Setting \( M = \frac{C_2}{c_1}e^{(a_1 + a_2)\psi t} \), we get the desired result. \( \square \)

**Example 1.** Consider the one-dimensional stochastic nonlinear system driven by G-Brownian motion
\[ dx(t) = x(t) \sin t dt + (4 + \sin t)x(t) dB(t) + \sqrt{2 + \cos t}x(t) dB(t), \quad t \geq 0, \quad (14) \]

where \( B(t) \) is \( \mathbb{R} \)-valued G-Brownian motion obeying \( N(0, [\frac{1}{2}, 1]) \). Assuming \( V(t, x) = |x|^2 \), we have
\[
\begin{align*}
V_x(t, x(t))f(t, x(t)) & = 2|x(t)|^2 \sin t, \\
V_x(t, x(t))g(t, x(t)) & = 2|x(t)|^2(4 + \sin t), \\
V_{xx}(t, x(t))\sigma^2(t, x(t)) & = 2|x(t)|^2(2 + \cos t)
\end{align*}
\]

and
\[
LV(t, x(t)) = -2|x(t)|^2 + G(12|x(t)|^2 + 2|x(t)|^2) = 5|x(t)|^2
\]

Therefore, the (14) is not exponentially stable in mean square. Now, substituting the aperiodically intermittent controller \( h(t) \) into the system (14), we assume the control of the following system
\[ dy(t) = y(t) \sin t dt + h(s)(4 + \sin t)y(t) dB(t) + h(s)\sqrt{2 + \cos t}y(t) dB(t), \quad t \geq 0, \quad (15) \]

For any \( t \in [t_i, s_i) \), we can conclude
\[ LV(t, y(t))) \leq 2|y(t)|^2 + G(-12|y(t)|^2 + 6|y(t)|^2) = -|y(t)|^2. \]

If \( t \in [s_i, t_{i+1}) \), we can obtain
\[ LV(t, y(t))) \leq 2|y(t)|^2. \]

Let \( C_1 = 1, C_2 = 5, C_3 = \sqrt{2}, a_1 = 1, a_2 = 2, \) then, \( \psi \in (0, \frac{1}{2}) \), from Theorem 1, then the system (15) is stable.

**4. Conclusions**

The paper studied the \( p \)-th exponential stability for the mild solution of stochastic differential equations driven by G-Brownian motion. By using an aperiodically intermittent control, added to the drift coefficients and G-Lyapunov function, the desired result is obtained under suitable conditions. Moreover, the length of intermittent intervals is given. Finally, an example is presented to introduce the effectiveness of the results.
Funding: This research was funded by the Foundation for Excellent Young Talents Fund Program of Higher Education Institutions of Anhui Prov (No. gxyq2018102), Natural Science Foundation of Anhui Colleges (No. KJ2020A0731), Research Projects of Humanities and Social Science of Anhui Province (SK2020A0527), Ministry of Education Cooperative Education Project (No. 202002165040), Consulting projects entrusted by enterprises (No. 2020xhx119) for the financial support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request.

Acknowledgments: The authors thank the reviewers and editors for their careful evaluation and their fruitful comments.

Conflicts of Interest: The authors declare no conflict of interest.

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