

Inertial split projection and contraction method for pseudomonotone variational inequality problem in Banach spaces

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ABSTRACT. In this article, we introduce a Halpern iterative method together with an inertial projection and contraction method for finding an approximate solution of variational inequality problem involving pseudomonotone mapping which also solves split common fixed point problem of Bregman demigeneralized mapping and Bregman strongly nonexpansive mapping in the framework of p -uniformly convex and uniformly smooth real Banach spaces. Using our iterative method, we establish a strong convergence result for approximating the solution of the aforementioned problems and state some consequences of our main result. The result discussed in this article extends and complements many related results in the literature.

1. INTRODUCTION

Let C be a nonempty, closed and convex subset of a real Banach space E and let E^* denote the dual space of E . The Variational Inequality Problem (in short VIP) is to find $x \in C$ such that

$$(1.1) \quad \langle Ax, y - x \rangle \geq 0, \quad \forall y \in C,$$

where $A : C \rightarrow E^*$ is a nonlinear mapping. We denote by $VI(C, A)$ the set of solutions of (1.1).

Variational inequality theory introduced by Stampacchia and Fichera [24, 36] independently, in early sixties in mechanics and potential theory respectively provides the natural, unified and efficient framework for a general treatment of a wide class of unrelated linear and nonlinear problems arising in elasticity, economics, transportation, optimization, control theory and engineering sciences (see [9, 10]).

The development of variational inequality theory can be viewed as the simultaneous pursuit of two different lines of research. The first aspect reveals the fundamental facts on the qualitative behavior of solutions to important classes of problems. On the other hand, it allows us to develop highly efficient and powerful numerical methods to solve, for instance, obstacle, unilateral, free and moving boundary value problems.

In 1985, Pang [34] showed that a variety of equilibrium models, for example, the traffic equilibrium problem, the spatial equilibrium problem, the Nash equilibrium problem and the general equilibrium programming problem can be uniformly modelled as a VIP. It is well-known that $VI(C, A)$ is equivalent to the fixed point problem:

$$\text{find } x^* \in C \text{ such that } x^* = P_C(x^* - \tau Ax^*),$$

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where τ is any positive real number and P_C is a metric projection onto C . Recently, many methods have been applied for finding $VI(C, A)$, (see [2, 5, 7, 12, 13]). The simplest one is the projection method, which is called the Gradient Projection Method (in short, GPM). The basic idea of extending the GPM for solving problem of minimizing $f(x)$ subject to $x \in C$ is given by

$$(1.2) \quad x_{n+1} = P_C(x_n - \alpha_n \nabla f(x_n)), \quad n \geq 0,$$

where $\{\alpha_n\}$ is a positive real sequence satisfying certain condition and ∇f is the gradient function. An immediate extension of the method in (1.2) is the GPM which requires substituting the gradient function with operator F so that we can generate a sequence $\{x_n\}$ in the following manner:

$$x_{n+1} = P_C(x_n - \alpha_n Fx_n), \quad \forall n \geq 0.$$

However, the convergence of this method requires a slightly strong assumption that the operators are inverse strongly monotone or strongly monotone. In order to relax this condition, Korpelvich [29] and Antipin [6] proposed the Extragradient Method (in short EM) in finite dimensional Euclidean spaces for a monotone and L -Lipschitz continuous mapping A as follows:

$$(1.3) \quad \begin{cases} x_0 \in C, \tau > 0, \\ y_n = P_C(x_n - \tau Ax_n), \\ x_{n+1} = P_C(x_n - \tau Ay_n), \quad \forall n \geq 1, \end{cases}$$

where $\tau \in (0, \frac{1}{L})$. The sequence $\{x_n\}$ generated by EM (1.3) converges to an element of $VI(C, A)$ provided $VI(C, A)$ is nonempty. It should be noted that in EM, one needs to calculate two projections onto the feasible set C in each iteration. If the set C is not so simple, then the EM becomes very difficult and its implementation is costly. In addition, the convergence of the method (1.3) requires prior estimate of the Lipschitz constant which is often difficult to estimate and we emphasize that the stepsize defined by the process is too small and reduces the convergence rate of the method. To the best of our knowledge, there are some methods to overcome these drawbacks. The first one is the subgradient extragradient method (SEGM) proposed by *Censor et al.* [13], in which the second projection onto C is replaced by a projection onto a specific constructible half-space. Their method is of the form:

$$(1.4) \quad \begin{cases} y_n = P_C(x_n - \tau Fx_n), \\ T_n = \{w \in H : \langle x_n - \tau Fx_n - y_n, w - y_n \rangle \leq 0\}, \\ x_{n+1} = P_{T_n}(x_n - \tau Fy_n), \quad \forall n \geq 0, \end{cases}$$

where $\tau \in (0, \frac{1}{L})$.

The second one is the method proposed by Tseng in [38]. His method is of the form:

$$(1.5) \quad \begin{cases} y_n = P_C(x_n - \tau Fx_n), \\ x_{n+1} = y_n - \lambda(Fy_n - Fx_n), \quad \forall n \geq 0, \end{cases}$$

where $\tau \in (0, \frac{1}{L})$.

The third one is the projection and contraction method (PCM) proposed by He [25] for

solving VIP. The PCM can be summarized as follows:

$$(1.6) \quad \begin{cases} x_0 \in H, \\ y_n = P_C(x_n - \tau Fx_n), \\ d(x_n, y_n) := (x_n - y_n) - \tau(Fx_n - Fy_n), \\ x_{n+1} = x_n - \gamma\eta_n d(x_n, y_n), \forall n \geq 0, \end{cases}$$

where $\gamma \in (0, 2), \tau \in (0, \frac{1}{L})$ and

$$\eta_n := \frac{\phi(w_n, y_n)}{\|d(w_n, y_n)\|^2}, \quad \phi(w_n, y_n) := \langle w_n - y_n, d(w_n, y_n) \rangle, \quad \forall n \geq 0.$$

It is worth mentioning that the SEGM, TM and PCM described above need only to calculate one projection onto C in each iteration which may improve the performance of the algorithms. Also, the SEGM, TM and PCM have received great attention by many authors, who improved it in various ways (see [2, 7, 13, 14, 18, 21, 22, 23, 27, 28, 38] and the references contained in). We emphasize that the first two methods (SEGM and TM) have been considered by authors extensively in the settings of real Hilbert and Banach spaces, but no result on PCM in the literature can be found in the framework of Banach spaces.

Question: Can we employ the PCM for solving VIP in the setting of Banach spaces?

One of the best ways to speed up the convergence rate of iterative algorithms is to combine the iterative scheme with the inertial term. This term which is represented by $\theta_n(x_n - x_{n-1})$, is a remarkable tool for improving the performance of algorithms and it is known to have some nice convergence characteristics. Thus, there are growing interests by authors working in this direction (see [1, 2, 3, 4, 17, 26]). The idea of inertial extrapolation method was first introduced by Polyak [35] and was inspired by an implicit discretization of a second-order-in-time dissipative dynamical system, so-called "Heavy Ball with Friction".

$$(1.7) \quad v''(t) + \gamma v'(t) + \nabla f(v(t)) = 0,$$

where $\gamma > 0$ and $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is differentiable. System (1.7) is discretized so that, having the terms x_{n-1} and x_n , the next term x_{n+1} can be determined using

$$(1.8) \quad \frac{x_{n-1} - 2x_n + x_{n-1}}{j^2} + \gamma \frac{x_n - x_{n-1}}{j} + \nabla f(x_n) = 0, \quad n \geq 1,$$

where j is the step-size. Equation (1.8) yields the following iterative algorithm:

$$(1.9) \quad x_{n+1} = x_n + \beta(x_n - x_{n-1}) - \alpha \nabla f(x_n), \quad n \geq 1,$$

where $\beta = 1 - \gamma_j, \alpha = j^2$ and $\beta(x_n - x_{n-1})$ is called the inertial extrapolation term which is intended to speed up the convergence of the sequence generated by (1.9). Alvarez and Attouch [8] also employed the inertial extrapolation method to the setting of a general maximal monotone operator using the proximal point algorithm (PPA), which is called the inertial PPA, and is of the form:

$$(1.10) \quad \begin{cases} y_n = x_n + \theta_n(x_n - x_{n-1}), \\ x_{n+1} = (I + r_n B)^{-1} y_n, \quad n > 1. \end{cases}$$

They proved that if $\{r_n\}$ is non-decreasing and $\{\theta_n\} \subset [0, 1)$ with

$$(1.11) \quad \sum_{n=1}^{\infty} \theta_n \|x_n - x_{n-1}\|^2 < \infty,$$

then the iterative Algorithm (1.10) converges weakly to a zero of B . More precisely, condition (1.11) is true for $\theta_n < \frac{1}{3}$. Here θ_n is an extrapolation factor. Very recently, *Dong et al.* [23] proposed an inertial projection and contraction method (IPCM) of the form:

$$(1.12) \quad \begin{cases} x_0, x_1 \in H, \\ w_n = x_n + \alpha_n(x_n - x_{n-1}), \\ y_n = P_C(w_n - \tau Fw_n), \\ d(w_n, y_n) = (w_n - y_n) - \tau(Fw_n - Fy_n), \\ x_{n+1} = w_n - \gamma\eta_n d(w_n, y_n), \forall n \geq 0, \end{cases}$$

where $\gamma \in (0, 2)$, $\tau \in (0, \frac{1}{L})$ and

$$(1.13) \quad \eta_n := \begin{cases} \frac{\phi(w_n, y_n)}{\|d(w_n, y_n)\|^2}, & \text{if } d(w_n, y_n) \neq 0, \\ 0, & \text{if } d(w_n, y_n) = 0, \end{cases}$$

where $\phi(w_n, y_n) := \langle w_n - y_n, d(w_n, y_n) \rangle$. Under suitable conditions, they established that the sequence $\{x_n\}$ generated by (1.12) converges weakly to an element of $VI(C, F)$. In the setting of Banach space, several authors have modified the inertial extrapolation method without the computation of the difference between the norm of the two adjacent iterates x_n and x_{n-1} . Approximating solutions of different optimization problems with inertial extrapolation method using either viscosity and Halpern method in the setting of Banach space requires the modification of inertial term due to the geometry of the space (see [3, 7, 33, 37] and the references contained in). The only case where the inertial term is not modified is when the hybrid and shrinking methods are employed in the setting of Banach space, (see [2, 17, 26]). To the best of our knowledge, there is no result on inertial extrapolation method without modification using Halpern method in the setting of Banach spaces.

Question 2: Can we introduce an inertial Halpern method without the computation of the difference between the norm of the two adjacent iterates x_n and x_{n-1} for finding the solution of VIP in the setting of p -uniformly convex real Banach space which are also uniformly smooth?

Motivated by the results of [6, 14, 21, 22, 28, 38] and other related results in literature, we proposed a Halpern inertial iterative algorithm with projection and contraction method for approximating the solution of split variational inequality problem involving a pseudomonotone operator, fixed points of Bregman demigeneralized mapping and Bregman strongly nonexpansive mapping in the setting of p -uniformly convex real Banach space which is also uniformly smooth. Using our iterative method, we establish a strong convergence result for approximating the solution of the aforementioned problems. We emphasize that our iterative method is design in such a way that it does not require prior knowledge of the operator norm. We present some numerical examples to show the efficiency of our result. The result green discussed in this paper extends and complements many related results in the literature.

We state some known and useful results which will be needed in the proof of our main theorem. In the sequel, we denote strong and weak convergence by " \rightarrow " and " \rightharpoonup ". respectively.

Let E be a Banach space with the dual E^* . An operator $A : E \rightarrow E^*$ is said to be p -Lipschitz, if

$$\|Ax - Ay\| \leq L\|x - y\|^p \forall x, y \in E,$$

where $L \geq 0$ and $p \in [1, \infty)$ are two constants. If $p = 1$, the operator A is said to be L -Lipschitz.

Let $C \subseteq E$ be a nonempty set. Then a mapping $A : C \rightarrow E^*$ is called

- (a) monotone on C , if $\langle Ax - Ay, x - y \rangle \geq 0$ for all $x, y \in C$;
- (b) pseudomonotone on C , if for all $x, y \in E$, $\langle Ax, y - x \rangle \geq 0 \implies \langle Ay, y - x \rangle \geq 0$;
- (c) weakly sequentially continuous if for any $\{x_n\} \subset C$ such that $x_n \rightharpoonup x$ implies $Ax_n \rightharpoonup Ax$.

Let E be a real Banach space and $f : E \rightarrow \mathbb{R}$. Then f is called:

- (i) Gâteaux differentiable at $x \in E$, denoted by $f'(x)$ or $\nabla f(x)$, if there exists an element y of E , such that

$$\lim_{t \rightarrow 0} \frac{f(x + ty) - f(x)}{t} = \langle y, f'(x) \rangle, \forall y \in E.$$

f is Gâteaux differentiable on E if f is Gâteaux differentiable at every $x \in E$;

- (ii) weakly lower semicontinuous at $x \in E$, if $x_k \rightharpoonup x$ implies $f(x) \leq \liminf_{k \rightarrow \infty} f(x_k)$.
 f is weakly lower semicontinuous on E , if f is weakly lower semicontinuous at every $x \in E$.

Let $K(E) := \{x \in E : \|x\| = 1\}$ denote the unit sphere of E . The modulus of convexity is the function $\delta_E : (0, 2] \rightarrow [0, 1]$ defined by

$$\delta_E(\epsilon) = \inf \left\{ 1 - \frac{\|x + y\|}{2} : x, y \in K(E), \|x - y\| \geq \epsilon \right\}.$$

The space E is said to be uniformly convex if $\delta_E(\epsilon) > 0$ for all $\epsilon \in (0, 2]$. Let $p > 1$. Then E is said to be p -uniformly convex (or to have a modulus of convexity of power type p) if there exists $c_p > 0$ such that $\delta_E(\epsilon) \geq c_p \epsilon^p$ for all $\epsilon \in (0, 2]$. Note that every p -uniformly convex space is uniformly convex. The modulus of smoothness of E is the function $\rho_X : \mathbb{R}^+ := [0, \infty) \rightarrow \mathbb{R}^+$ defined by

$$\rho_X(\tau) = \sup \left\{ \frac{\|x + \tau y\| + \|x - \tau y\|}{2} - 1 : x, y \in K(E) \right\}.$$

The space E is said to be uniformly smooth if $\frac{\rho_E(\tau)}{\tau} \rightarrow 0$ as $\tau \rightarrow 0$. Let $q > 1$. Then a Banach space E is said to be q -uniformly smooth if there exists $\kappa_q > 0$ such that $\rho_E(\tau) \leq \kappa_q \tau^q$ for all $\tau > 0$. It is known that E is p -uniformly convex if and only if E^* is q -uniformly smooth, where p and q satisfy $\frac{1}{p} + \frac{1}{q} = 1$, (see [19]).

Let $p > 1$ be a real number, the generalized duality mapping $J_p^E : E \rightarrow 2^{E^*}$ is defined by

$$J_p^E(x) = \{\bar{x} \in E^* : \langle x, \bar{x} \rangle = \|x\|^p, \|\bar{x}\| = \|x\|^{p-1}\},$$

where $\langle \cdot, \cdot \rangle$ denotes the duality pairing between elements of E and E^* . In particular, if $p = 2$, then J_2^E is called the normalized duality mapping. If E is p -uniformly convex and uniformly smooth, then E^* is q -uniformly smooth and uniformly convex. In this case, the generalized duality mapping J_p^E is one-to-one, single-valued and satisfies $J_p^E = (J_q^{E^*})^{-1}$, where $J_q^{E^*}$ is the generalized duality mapping of E^* . Furthermore, if E is uniformly smooth, then the duality mapping J_p^E is norm-to-norm uniformly continuous on bounded subsets of E , (see [20] for more details).

If $f : E \rightarrow (-\infty, +\infty]$ is a proper, lower semicontinuous and convex function, then the Fenchel conjugate of f denoted by $f^* : E^* \rightarrow (-\infty, +\infty]$ is defined as

$$f^*(x^*) = \sup\{\langle x^*, x \rangle - f(x) : x \in E, x^* \in E^*\}.$$

Let the domain of f be denoted by $\text{dom} f = \{x \in E : f(x) < +\infty\}$. For any $x \in \text{int}(\text{dom} f)$ and $y \in E$, we denote and define the right-hand derivative of f at x in the direction of y by

$$f^0(x, y) = \lim_{t \rightarrow 0^+} \frac{f(x + ty) - f(x)}{t}.$$

Definition 1.1. [11] Let $f : E \rightarrow (-\infty, +\infty]$ be a convex and Gâteaux differentiable function. The function $\Delta_f : E \times E \rightarrow [0, +\infty)$ defined by

$$(1.14) \quad \Delta_f(x, y) := f(y) - f(x) - \langle \nabla f(x), y - x \rangle$$

is called the Bregman distance with respect to f , where $\langle \nabla f(x), y \rangle = f^0(x, y)$.

It is well-known that Bregman distance function Δ_f does not satisfy the properties of a metric function, because Bregman function Δ_f fails to satisfy the symmetric and triangular inequality properties. Moreover, it is well-known that the duality mapping J_p^E is the sub-differential of the functional $f_p(\cdot) = \frac{1}{p} \|\cdot\|^p$ for $p > 1$, (see [16]). Using (1.14), one can show that the following equality called three-point identity is satisfied:

$$(1.15) \quad \Delta_p(x, y) + \Delta_p(y, z) - \Delta_p(x, z) = \langle J_p^E(z) - J_p^E(y), x - y \rangle, \forall x, y, z \in E.$$

In addition, if $f(x) = \frac{1}{p} \|x\|^p$, where $\frac{1}{p} + \frac{1}{q} = 1$, then we obtain

$$(1.16) \quad \begin{aligned} \Delta_f(x, y) &= \Delta_p(x, y) = \frac{1}{p} \|y\|^p - \frac{1}{p} \|x\|^p - \langle y - x, J_p^E(x) \rangle \\ &= \frac{1}{p} \|y\|^p - \frac{1}{p} \|x\|^p - \langle y, J_p^E(x) \rangle + \langle x, J_p^E(x) \rangle \\ &= \frac{1}{p} \|y\|^p - \frac{1}{p} \|x\|^p - \langle y, J_p^E(x) \rangle + \|x\|^p \\ &= \frac{1}{p} \|y\|^p + \frac{1}{q} \|x\|^p - \langle y, J_p^E(x) \rangle. \end{aligned}$$

Let $T : C \rightarrow C$ be a nonlinear mapping,

- (i) a point $p \in C$ is called an asymptotic fixed point of T , if C contains a sequence $\{x_n\}$ which converges weakly to p such that $\lim_{n \rightarrow \infty} \|Tx_n - x_n\| = 0$. We denote by

$\hat{F}(T)$ the set of asymptotic fixed points of T ;

- (ii) T is said to be Bregman relatively nonexpansive, if

$$\hat{F}(T) = F(T) \neq \emptyset \text{ and } \Delta_p(u, Tx) \leq \Delta_p(u, x), \forall x \in C, u \in F(T).$$

- (iii) T is said to be Bregman firmly nonexpansive mapping (BFNE) if

$$\langle J_p^E(Tx) - J_p^E(Ty), Tx - Ty \rangle \leq \langle J_p^E(x) - J_p^E(y), Tx - Ty \rangle, \forall x, y \in C,$$

- (iv) T is said to be Bregman strongly nonexpansive mapping (BSNE) with $\hat{F}(T) \neq \emptyset$ if

$$\Delta_p(y, Tx) \leq \Delta_p(y, x), \forall y \in \hat{F}(T)$$

and for any bounded sequence $\{x_n\}_{n \geq 1} \subset C$,

$$\lim_{n \rightarrow \infty} (\Delta_p(y, x_n) - \Delta_p(y, Tx_n)) = 0$$

implies

$$\lim_{n \rightarrow \infty} \Delta_p(Tx_n, x_n) = 0.$$

Let C be a nonempty, closed and convex subset of E . The metric projection

$$P_C x := \arg \min_{y \in E} \|x - y\|, \quad x \in E,$$

is the unique minimizer of the norm distance, which can be characterized by a variational inequality:

$$(1.17) \quad \langle J_E^p(x - P_C x), z - P_C x \rangle \leq 0, \quad \forall z \in C.$$

Also, the Bregman projection from E onto C denoted by Π_C satisfies the property

$$(1.18) \quad \Delta_p(x, \Pi_C(x)) = \inf_{y \in C} \Delta_p(x, y), \quad \forall x \in E.$$

[19] Let C be a nonempty, closed and convex subset of a p -uniformly convex and uniformly smooth Banach space E and $x \in E$. Then the following assertions hold:
 $z = \Pi_C x$ if and only if

$$(1.19) \quad \langle J_E^p(x) - J_E^p(z), y - z \rangle \leq 0, \quad \forall y \in C;$$

and

$$(1.20) \quad \Delta_p(\Pi_C x, y) + \Delta_p(x, \Pi_C x) \leq \Delta_p(x, y), \quad \forall y \in C.$$

We now give some results that will help us in the proof of our main theorem.

Lemma 1.1. [15] *If E is a p -uniformly convex Banach space with $p \geq 2$, then there exists $K > 0$ such that for all $x, y \in E$, the following inequalities hold:*

$$(1.21) \quad \langle J_E^p(x) - J_E^p(y), x - y \rangle \geq K \|x - y\|^p,$$

and

$$(1.22) \quad \|x - y\| \leq \left(\frac{1}{K}\right)^{\frac{1}{(p-1)}} \|J_E^p(x) - J_E^p(y)\|^{1/(p-1)}.$$

Lemma 1.2. [16] *Let E be a Banach space and $x, y \in E$. If E is q -uniformly smooth, then there exists $C_q > 0$ such that*

$$\|x - y\|^q \leq \|x\|^q - q \langle J_E^q(x), y \rangle + C_q \|y\|^q.$$

Lemma 1.3. [39] *Let E be a p -uniformly convex Banach space, the metric and Bregman distance have the following relation for all $x, y \in E$*

$$(1.23) \quad \pi_p \|x - y\|^p \leq \Delta_p(x, y) \leq \langle x - y, J_E^p(x) - J_E^p(y) \rangle,$$

where $\pi_p > 0$ is a fixed number and for any $q > 1$, if $\frac{1}{p} + \frac{1}{q} = 1$, by Young's inequality, we have

$$(1.24) \quad \begin{aligned} \langle J_E^p(x), y \rangle &\leq \|J_E^p(x)\| \|y\| &\leq \frac{1}{q} \|J_E^p(x)\|^q + \frac{1}{p} \|y\|^p \\ &= \frac{1}{q} (\|x\|^{p-1})^q + \frac{1}{p} \|y\|^p \\ &= \frac{1}{q} \|x\|^p + \frac{1}{p} \|y\|^p. \end{aligned}$$

Lemma 1.4. [16] Let $q > 1$ be a fixed real number and E be a smooth Banach space. Then E is q -uniformly smooth if and only if there exists a constant C_q such that for all $x, y \in E$, we have

$$(1.25) \quad \left\| \frac{x+y}{2} \right\|^q \geq \frac{1}{2} \|x\|^q + \frac{1}{2} \|y\|^q - 2^{-q} C_q \|x-y\|^q.$$

Putting $x = u - v$ and $y = u + v$ in (1.25), we get for all $u, v \in E$

$$(1.26) \quad \|u - v\|^q \leq 2(\|u\|^q + C_q \|v\|^q) - \|u + v\|^q \leq 2(\|u\|^q + C_q \|v\|^q).$$

Lemma 1.5. [40] Let E be a real p -uniformly convex and uniformly smooth Banach space. Let $V_p : E^* \times E \rightarrow [0, +\infty)$ be defined by

$$V_p(x^*, x) = \frac{1}{q} \|x^*\|^q - \langle x^*, x \rangle + \frac{1}{p} \|x\|^p, \quad \forall x \in E, x^* \in E^*.$$

Then the following assertions hold:

(i) V_p is nonnegative and convex in the first variable.

(ii) $\Delta_p(J_q^{E^*}(x^*), x) = V_p(x^*, x)$, $\forall x \in E, x^* \in E^*$.

(iii) $V_p(x^*, x) + \langle y^*, J_q^{E^*}(x^*) - x \rangle \leq V_p(x^* + y^*, x)$, $\forall x \in E, x^*, y^* \in E^*$.

Lemma 1.6. [19] Let E be a real p -uniformly convex and uniformly smooth Banach space. Suppose that $\{x_n\}$ and $\{y_n\}$ are bounded sequences in E . Then $\lim_{n \rightarrow \infty} \Delta_p(x_n, y_n) = 0$ implies $\lim_{n \rightarrow \infty} \|x_n - y_n\| = 0$.

Definition 1.2. [42] Let C be a nonempty subset of a p -uniformly convex ($0 < p < \infty$) and uniformly smooth real Banach space E . A mapping $T : C \rightarrow E$ is called θ -Bregman demigeneralized type with respect to p , if $F(T) \neq \emptyset$ and there exists a real number θ such that

$$(1.27) \quad \Delta_p(x, Tx) \leq \theta \langle J_E^p(x) - J_E^p(Tx), x - x^* \rangle \quad \forall x \in E, x^* \in F(T).$$

Lemma 1.7. [42] Let C be a nonempty subset of a p -uniformly convex and uniformly smooth real Banach space E . Let $T : C \rightarrow E$ be a θ -Bregman demigeneralized type mapping with $\theta \in \mathbb{R}$. Then $F(T)$ is closed and convex.

Lemma 1.8. [30] Let E be a real reflexive Banach space and C a nonempty, closed and convex subset of E . Let A be a continuous pseudomonotone mapping from C into E^* . Then, $VI(C, A)$ is closed and convex. Furthermore, $x^* \in VI(C, A)$ if and only if $\langle Ax, x - x^* \rangle \geq 0$ for all $x \in C$.

Lemma 1.9. [41] Let $\{\alpha_n\}$ be a sequence of nonnegative real numbers, $\{\alpha_n\}$ be a sequence of real numbers in $(0, 1)$ with condition:

$$\sum_{n=1}^{\infty} \alpha_n = \infty$$

and $\{b_n\}$ be a sequence of real numbers. Assume that

$$a_{n+1} \leq (1 - \alpha_n) a_n + \alpha_n b_n, \quad \forall n \geq 1.$$

If $\limsup_{k \rightarrow \infty} b_{n_k} \leq 0$ for every subsequence $\{a_{n_k}\}$ of $\{a_n\}$ satisfying the condition

$$\liminf_{k \rightarrow \infty} (a_{n_k+1} - a_{n_k}) \geq 0,$$

then $\lim_{n \rightarrow \infty} a_n = 0$.

In the sequel, we assume the following hold.

Assumption 1.1. (C1) E_1 and E_2 are p -uniformly convex real Banach spaces which are also uniformly smooth and C is a nonempty closed and convex subset of E_1 .

- (C2) $A : C \rightarrow E_1^*$ is pseudomonotone and $(p - 1) - L$ -Lipschitz continuous on E_1 .
- (C3) A is weakly sequentially continuous, that is for any $\{x_n\} \subset E_1$, we have $x_n \rightharpoonup x^*$ implies $Ax_n \rightharpoonup Ax^*$.
- (C4) $B : E_1 \rightarrow E_2$ is a bounded linear operator with adjoint $B^* : E_2^* \rightarrow E_1^*$ and $S : E_2 \rightarrow E_2$ is a ξ -Bregman demigeneralized type mapping which is demiclosed at 0 such that $F(S) \neq \emptyset$, where $\xi \in (0, \infty)$ with $\frac{1}{\xi} \geq 1 - \eta$, $\eta \in (-\infty, 0]$ and $T : E_1 \rightarrow E_1$ is a Bregman strongly nonexpansive mapping.
- (C5) $\{\mu_n\}$ is a positive sequence in $(0, \frac{p\pi_p}{2^{p-1}})$, where π_p is defined in (1.23), $\mu_n = o(\alpha_n)$, where α_n is a sequence in $(0, 1)$ such that $\lim_{n \rightarrow \infty} \alpha_n = 0$ and $\sum_{n=1}^{\infty} \alpha_n = \infty$, and $\{\beta_n\}$, $\{\gamma_n\}$ are sequences in $(0, 1)$ such that $\alpha_n + \beta_n + \gamma_n = 1$, $\beta_n \in (a, b) \subset (0, 1)$ and $\gamma_n \in (c, d) \subset (0, 1)$ for all $n \geq 1$.
- (C6) Denote the set of solution by $\Gamma := \text{SOL}(A, C) \cap B^{-1}(F(S)) \cap F(T)$ and is assumed to be nonempty. Then Γ is closed and convex.

Next, we introduce an inertial extrapolation with projection and contraction method for finding common solution of fixed point problem and pseudomonotone variational inequality problem:

Algorithm 1.2. Initialization: Choose $x_0, x_1 \in E_1$ to be arbitrary and $\theta \in (0, \pi_p)$, $K^* > 0$.

Iterative Steps: Calculate x_{n+1} as follows:

Step 1. Given the iterates x_{n-1} and x_n for each $n \geq 1$, $\theta > 0$, choose θ_n such that $0 \leq \theta_n \leq \bar{\theta}_n$, where

$$(1.28) \quad \bar{\theta}_n = \begin{cases} \min\{\theta, \frac{\mu_n}{\|J_{E_1}^p(x_n) - J_{E_1}^p(x_{n-1})\|}\}, & \text{if } x_n \neq x_{n-1}, \\ \theta, & \text{otherwise.} \end{cases}$$

Step 2. Compute

$$(1.29) \quad \begin{cases} y_n = J_{E_1^*}^q[J_{E_1}^p(x_n) + \theta_n(J_{E_1}^p(x_n) - J_{E_1}^p(x_{n-1}))], \\ w_n = \Pi_C(J_{E_1^*}^q[J_{E_1}^p(y_n) - \tau A(y_n)]). \end{cases}$$

If $w_n = y_n$ for some $n \geq 1$, then stop and is a solution of the problem (VIP). Otherwise go to step 3.

Step 3. Compute

$$(1.30) \quad \begin{cases} v_n = J_{E_1^*}^q[J_{E_1}^p(y_n) - \rho_n J_{E_1}^p(d_n)], \\ d_n = J_{E_1^*}^q(J_{E_1}^p(y_n) - J_{E_1}^p(w_n) - \tau(A(y_n) - A(w_n))). \end{cases}$$

where

$$(1.31) \quad \rho_n^{q-1} = K^* \frac{\|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q}{\|J_{E_1}^p d_n\|^q}, \text{ if } d_n \neq 0; \text{ otherwise } \rho_n = 0$$

$$(1.32) \quad \text{and } \langle J_{E_1}^p d_n, y_n - w_n \rangle \geq K^* \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q.$$

Step 4. Compute

$$(1.33) \quad \begin{cases} z_n = J_{E_1^*}^q(J_{E_1}^p(v_n) - \lambda_n B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(S(Bv_n)))) \\ x_{n+1} = J_{E_1}^q(\alpha_n J_{E_1}^p(u) + (1 - \alpha_n) J_{E_1}^p(Tz_n)), \end{cases}$$

where, for any fixed $\epsilon > 0$, the step λ_n is chosen as follows:

$$(1.34) \quad 0 < \epsilon \leq \lambda_n \leq \left(\frac{\pi_p q \|Bv_n - SBv_n\|^p}{C_q \xi \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q} - \epsilon \right)^{\frac{1}{p-1}},$$

if $Bv_n \neq SBv_n$, otherwise $\lambda_n = (\lambda > 0)$. Set $n := n + 1$ and return to **Step 1**.

Lemma 1.10. *If $y_n = w_n$ or $d_n = 0$ in Algorithm 1.2, then $y_n \in VI(C, A)$.*

Proof. Since A is $(p-1)$ - L -Lipschitz continuous with constant $L > 0$, from (1.30), (1.22) and (1.26), we get

$$(1.35) \quad \begin{aligned} \|J_{E_1}^p d_n\|^q &= \|J_{E_1}^p y_n - J_{E_1}^p w_n - \tau[Ay_n - Aw_n]\|^q \\ &\leq 2 \left(\|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q + C_q \tau^q \|Ay_n - Aw_n\|^q \right) \\ &\leq 2 \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q + 2C_q \tau^q [L \|y_n - w_n\|^{(p-1)}]^q \\ &\leq 2 \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q + 2C_q \tau^q L^q \left(\frac{1}{K} \right)^q \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q \\ &= 2 \left(1 + C_q \left(\frac{\tau L}{K} \right)^q \right) \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q. \end{aligned}$$

Also

$$(1.36) \quad \begin{aligned} \|J_{E_1}^p d_n\|^q &= \|J_{E_1}^p y_n - J_{E_1}^p w_n - \tau[Ay_n - Aw_n]\|^q \\ &\geq 2^{-1} \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q - C_q \tau^q \|Ay_n - Aw_n\|^q \\ &\geq 2^{-1} \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q - C_q \tau^q [L \|y_n - w_n\|^{(p-1)}]^q \\ &\geq 2^{-1} \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q - C_q \tau^q L^q \left(\frac{p}{c^2} \right)^q \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q \\ &= \left(\frac{1}{2} - C_q \left(\frac{\tau L}{K} \right)^q \right) \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q. \end{aligned}$$

Combining (1.35) and (1.36), we obtain

$$(1.37) \quad \left(\frac{1}{2} - C_q \tau^q L^q \left(\frac{1}{K} \right)^q \right)^{\frac{1}{q}} \|J_{E_1}^p y_n - J_{E_1}^p w_n\| \leq \|J_{E_1}^p d_n\| \leq 2 \left(1 + C_q \tau^q L^q \left(\frac{1}{K} \right)^q \right)^{\frac{1}{q}} \|J_{E_1}^p y_n - J_{E_1}^p w_n\|$$

thus, $J_{E_1}^p y_n = J_{E_1}^p w_n \Rightarrow y_n = w_n$ if and only if $J_{E_1}^p d_n = 0$. Hence, if $y_n = w_n$ or $d_n = 0$, we get

$$y_n = P_C(y_n - \tau Ay_n).$$

□

Lemma 1.11. *Let $\{x_n\}$ be the sequence generated by Algorithm 1.2 under Assumption 1.1. Then, $\{x_n\}$ is bounded.*

Proof. Let $x^* \in \Gamma$, since $w_n \in C$, it follows that $\langle Ax^*, w_n - x^* \rangle \leq 0$, thus by pseudomonotonicity of A , we get

$$(1.38) \quad \langle Aw_n, w_n - x^* \rangle \leq 0.$$

Also, by definition of w_n , i.e. $w_n := \Pi_C[J_{E_1}^q(J_{E_1}^p y_n - \tau Ay_n)]$, letting $J_{E_1}^p b_n := J_{E_1}^p y_n - \tau Ay_n$, then $w_n = \Pi_C z_n$, by (1.19), we get

$$\langle J_{E_1}^p z_n - J_{E_1}^p w_n, w_n - x^* \rangle \geq 0$$

which implies

$$(1.39) \quad \langle J_{E_1}^p y_n - \tau Ay_n - J_{E_1}^p w_n, w_n - x^* \rangle \geq 0.$$

Combining (1.38) and (1.40), we obtain

$$\langle J_{E_1}^p y_n - J_{E_1}^p w_n - \tau(Ay_n - Aw_n), w_n - x^* \rangle \geq 0.$$

Hence

$$(1.40) \quad \langle J_E^p d_n, w_n - x^* \rangle \geq 0.$$

Now, by Lemma 1.2 and 1.5, and relations (1.31), (1.32), (1.40), (1.22) and (1.23), we get

$$\begin{aligned} \Delta_p(v_n, x^*) &= \Delta_p(J_{E_1^*}^q(J_{E_1}^p y_n - \rho_n J_{E_1}^p d_n), x^*) \\ &= V_p(J_{E_1}^p y_n - \rho_n J_{E_1}^p d_n, x^*) \\ &= \frac{1}{q} \|J_{E_1}^p y_n - \rho_n J_{E_1}^p(d_n)\|^q - \langle J_{E_1}^p y_n - \rho_n J_{E_1}^p(d_n), x^* \rangle + \frac{1}{p} \|x^*\|^p \\ &\leq \frac{1}{q} \|J_{E_1}^p y_n\|^q - \rho_n \langle J_{E_1}^p d_n, y_n \rangle + C_q q^{-1} \|\rho_n J_{E_1}^p d_n\|^q \\ &\quad - \langle J_{E_1}^p y_n, x^* \rangle + \rho_n \langle J_{E_1}^p d_n, x^* \rangle + \frac{1}{p} \|x^*\|^p \\ &= V_p(J_{E_1}^p y_n, x^*) - \rho_n \langle J_{E_1}^p(d_n), y_n - x^* \rangle + C_q q^{-1} \|\rho_n J_{E_1}^p(d_n)\|^q \\ &= \Delta_p(y_n, x^*) - \rho_n \langle J_{E_1}^p(d_n), y_n - w_n \rangle - \rho_n \langle J_{E_1}^p(d_n), w_n - x^* \rangle \\ &\quad + C_q q^{-1} \|\rho_n J_{E_1}^p(d_n)\|^q \\ &\leq \Delta_p(y_n, x^*) - \rho_n K \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q + C_q q^{-1} \|\rho_n J_{E_1}^p(d_n)\|^q \\ &\leq \Delta_p(y_n, x^*) - \|\rho_n J_{E_1}^p(d_n)\|^q + C_q q^{-1} \|\rho_n J_{E_1}^p(d_n)\|^q \\ &= \Delta_p(y_n, x^*) - (1 - C_q q^{-1}) \|\rho_n J_{E_1}^p(d_n)\|^q \\ (1.41) \quad &= \Delta_p(y_n, x^*) - (1 - C_q q^{-1}) \|J_{E_1}^p y_n - J_{E_1}^p v_n\|^q. \end{aligned}$$

From Bregman identity (1.15), we get

$$(1.42) \quad \Delta_p(y_n, x^*) = \Delta_p(x_n, x^*) - \Delta_p(x_n, y_n) + \langle J_{E_1}^p y_n - J_{E_1}^p x_n, y_n - x^* \rangle.$$

Since we have $y_n = J_{E_1^*}^q(J_{E_1}^p x_n + \theta_n(J_{E_1}^p x_n - J_{E_1}^p x_{n-1}))$, it follows from (1.23), (1.24) and (1.28) that

$$\begin{aligned} \langle J_{E_1}^p y_n - J_{E_1}^p x_n, y_n - x^* \rangle &\leq \|J_{E_1}^p y_n - J_{E_1}^p x_n\| \|y_n - x^*\| \\ &= \theta_n \|J_{E_1}^p x_n - J_{E_1}^p x_{n-1}\| \|y_n - x^*\| \\ &\leq \theta_n \|J_{E_1}^p x_n - J_{E_1}^p x_{n-1}\| \left[\frac{1}{p} \|y_n - x^*\|^p + \frac{1}{q} \right] \\ &\leq \frac{\theta_n}{p} \|J_{E_1}^p x_n - J_{E_1}^p x_{n-1}\| [2^{p-1} (\|x_n - y_n\|^p + \|x_n - x^*\|^p)] \\ &\quad + \frac{\theta_n}{q} \|J_{E_1}^p x_n - J_{E_1}^p x_{n-1}\| \\ (1.43) \quad &\leq \frac{2^{p-1} \mu_n}{p\pi_p} (\Delta_p(x_n, y_n) + \Delta_p(x_n, x^*)) + \frac{\mu_n}{q}. \end{aligned}$$

Combining (1.42) and (1.43), we get

$$(1.44) \quad \Delta_p(y_n, x^*) \leq \left(1 + \frac{2^{p-1} \mu_n}{p\pi_p}\right) \Delta_p(x_n, x^*) - \left(1 - \frac{2^{p-1} \mu_n}{p\pi_p}\right) \Delta_p(x_n, y_n) + \frac{\mu_n}{q}.$$

Indeed from the definition of (z_n) , Lemma 1.2 and 1.5, and relations (1.23) and (1.2), we get

$$\begin{aligned}
\Delta_p(z_n, x^*) &= \Delta_p(J_{E_1}^q(J_{E_1}^p(v_n) - \lambda_n B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))), x^*) \\
&= V_p(J_{E_1}^p(v_n) - \lambda_n B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n)), x^*) \\
&= \frac{1}{p} \|x^*\|^p - \langle J_{E_1}^p(v_n) - \lambda_n B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n)), x^* \rangle \\
&\quad + \frac{1}{q} \|J_{E_1}^p(v_n) - \lambda_n B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \\
&\leq \frac{1}{p} \|x^*\|^p - \langle J_{E_1}^p(v_n), x^* \rangle + \lambda_n \langle B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n)), x^* \rangle + \frac{1}{q} \left[\|J_{E_1}^p(v_n)\|^q \right. \\
&\quad \left. - \lambda_n q \langle B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n)), v_n \rangle + C_q \lambda_n^q \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \right] \\
&= \frac{1}{p} \|x^*\|^p + \frac{1}{q} \|v_n\|^p - \langle J_{E_1}^p(v_n), x^* \rangle - \lambda_n \langle J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n), Bv_n - Bx^* \rangle \\
&\quad + \frac{C_q \lambda_n^q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \\
&\leq \Delta_p(v_n, x^*) - \frac{\lambda_n}{\xi} \Delta_p(Bv_n, S(Bv_n)) + \frac{C_q \lambda_n^q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \\
(1.45) \quad &\leq \Delta_p(v_n, x^*) - \lambda_n \left(\frac{\pi_p}{\xi} \|Bv_n - SBv_n\|^p - \frac{C_q \lambda_n^{q-1}}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \right).
\end{aligned}$$

On the other hand from the step size λ_n in (1.34), we have

$$\lambda_n^{q-1} \leq \frac{\pi_p q \|Bv_n - SBv_n\|^p}{C_q \xi \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q} - \epsilon,$$

if and only if

$$(1.46) \quad \epsilon C_q \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \leq \frac{\pi_p q}{\xi} \|Bv_n - SBv_n\|^p - \lambda_n^{q-1} C_q \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q.$$

Thus with left side of λ_n in (1.34) and together with (1.46), we get

$$\begin{aligned}
\frac{\epsilon^2 C_q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q &\leq \frac{\lambda_n \epsilon C_q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \\
&\leq \lambda_n \left[\frac{\pi_p}{\xi} \|Bv_n - SBv_n\|^p \right. \\
(1.47) \quad &\quad \left. - \frac{\lambda_n^{q-1} C_q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q \right].
\end{aligned}$$

Combining (1.45) and (1.47), we obtain

$$(1.48) \quad \Delta_p(z_n, x^*) \leq \Delta_p(v_n, x^*) - \frac{\epsilon^2 C_q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q.$$

Hence, combining (1.41), (1.44) and (1.48), we obtain

$$\begin{aligned}
\Delta_p(z_n, x^*) &\leq \left(1 + \frac{2^{p-1} \mu_n}{p \pi_p}\right) \Delta_p(x_n, x^*) - \left(1 - \frac{2^{p-1} \mu_n}{p \pi_p}\right) \Delta_p(x_n, y_n) + \frac{\mu_n}{q} \\
(1.49) \quad &\quad - (1 - C_q q^{-1}) \|J_{E_1}^p y_n - J_{E_1}^p v_n\|^q - \frac{\epsilon^2 C_q}{q} \|B^*(J_{E_2}^p(Bv_n) - J_{E_2}^p(SBv_n))\|^q.
\end{aligned}$$

Since, from (C5) taking $\zeta \in \left(0, \frac{p\pi_p}{2^{p-1}}\right)$, there exists $n \in \mathbb{N}$ such that for all $n \geq N$

$$\frac{\mu_n 2^{p-1}}{p\pi_p} < \alpha_n \zeta.$$

For some constant $M > 0$, it which follows from (1.49) that

$$(1.50) \quad \Delta_p(z_n, x^*) \leq (1 + \alpha_n \zeta) \Delta_p(x_n, x^*) + \alpha_n M.$$

Using the definition of (x_{n+1}) , (1.50) and the fact that T is a Bregman strongly relative nonexpansive mapping, we obtain

$$(1.51) \quad \begin{aligned} \Delta_p(x_{n+1}, x^*) &= \Delta_p(J_{E_1^q}^q [\alpha_n J_{E_1^p}^p u + (1 - \alpha_n) J_{E_1^p}^p T z_n], x^*) \\ &\leq \alpha_n \Delta_p(u, x^*) + (1 - \alpha_n) \Delta_p(T z_n, x^*) \\ &\leq \alpha_n \Delta_p(u, x^*) + (1 - \alpha_n) \Delta_p(z_n, x^*) \\ &\leq \alpha_n \Delta_p(u, x^*) + (1 - \alpha_n) [(1 + \alpha_n \zeta) \Delta_p(x_n, x^*) + \alpha_n M] \\ &\leq \alpha_n \Delta_p(u, x^*) + [1 - \alpha_n (1 - \zeta)] \Delta_p(x_n, x^*) + \alpha_n M \\ &= [1 - \alpha_n (1 - \zeta)] \Delta_p(x_n, x^*) + \alpha_n (1 - \zeta) \frac{\Delta_p(u, x^*) + M}{1 - \zeta} \\ &\leq \max \left\{ \Delta_p(x_n, x^*), \frac{\Delta_p(u, x^*) + M}{1 - \zeta} \right\} \\ &\quad \vdots \\ &\leq \max \left\{ \Delta_p(x_N, x^*), \frac{\Delta_p(u, x^*) + M}{1 - \zeta} \right\}. \end{aligned}$$

By induction, we get

$$\Delta_p(x_n, x^*) \leq \max \left\{ \Delta_p(x_N, x^*), \frac{\Delta_p(u, x^*) + M}{1 - \zeta} \right\}, \text{ for all } n \geq N.$$

This implies that $\{\Delta_p(x_n, x^*)\}$ is bounded. From (1.23), we know that $\pi_p \|x_n - x^*\|^p \leq \Delta_p(x_n, x^*)$, so $\{x_n\}$ is also bounded. Hence $\{y_n\}$, $\{v_n\}$, $\{w_n\}$ and $\{z_n\}$ are bounded. Furthermore, combining (1.49) and (1.51), we get

$$\begin{aligned} \Delta_p(x_{n+1}, p) &\leq \alpha_n \Delta_p(u, x^*) + (1 - \alpha_n \zeta) \Delta_p(x_n, x^*) - (1 - \alpha_n \zeta) \Delta_p(x_n, y_n) + \alpha_n M \\ &\quad - (1 - C_q q^{-1}) \|J_{E_1^p}^p y_n - J_{E_1^p}^p v_n\|^q - \frac{\epsilon^2 C_q}{q} \|B^*(J_{E_2^p}^p(Bv_n) - J_{E_2^p}^p(SBv_n))\|^q. \end{aligned}$$

Thus

$$(1.52) \quad \Psi_n \leq \Delta_p(x_n, x^*) - \Delta_p(x_{n+1}, x^*) + \alpha_n M_1,$$

where $\Psi_n := (1 - \alpha_n \zeta) \Delta_p(x_n, y_n) + (1 - C_q q^{-1}) \|J_{E_1^p}^p y_n - J_{E_1^p}^p v_n\|^q + \frac{\epsilon^2 C_q}{q} \|B^*(J_{E_2^p}^p(Bv_n) - J_{E_2^p}^p(SBv_n))\|^q$ and $M_1 := \sup_{n \geq N} \{\Delta_p(x_n, x^*), M\}$. \square

Theorem 1.3. *The sequence $\{x_n\}$ generated by Algorithm 1.2 converges strongly to a point $x^* \in \Gamma$, where $x^* = \Pi_\Gamma u$.*

Proof. **Claim 1.** Let $\{y_n\}$ and $\{w_n\}$ be sequences generated by Algorithm 1.2 under Assumption 1.1. If there exist subsequences $\{y_{n_k}\}$ and $\{w_{n_k}\}$ of $\{y_n\}$ and $\{w_n\}$, respectively such that $\{y_{n_k}\}$ converges weakly to a point say z in H_1 and $\lim_{k \rightarrow \infty} \|w_{n_k} - y_{n_k}\| = 0$, then $z \in VI(C, A)$.

Claim 2.

$$(1.53) \quad \begin{aligned} \Delta_p(x_{n+1}, x^*) &\leq [1 - \alpha_n(1 - \zeta)]\Delta_p(x_n, x^*) \\ &+ \alpha_n(1 - \zeta) \left[(1 - \zeta)^{-1} \left(\langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n+1} - x^* \rangle + \frac{\mu_n}{\alpha_n} \right) \right]. \end{aligned}$$

Indeed, using Lemma 1.5 (ii), (iii), (1.49), (1.50) and $\mu_n = \circ(\alpha_n)$ in (C5), we get

$$\begin{aligned} \Delta_p(x_{n+1}, x^*) &= \Delta_p(J_{E_1}^q(\alpha_n J_{E_1}^p(u) + (1 - \alpha_n)J_{E_1}^p(z_n)), x^*) \\ &= V_p(\alpha_n J_{E_1}^p(u) + (1 - \alpha_n)J_{E_1}^p(z_n), x^*) \\ &\leq V_p(\alpha_n J_{E_1}^p(u) + (1 - \alpha_n)J_{E_1}^p(z_n) - \alpha_n(J_{E_1}^p(u) - J_{E_1}^p(x^*)), x^*) \\ &\quad - \langle J_{E_1}^q(\alpha_n J_{E_1}^p(u) + (1 - \alpha_n)J_{E_1}^p(z_n)) - x^*, -\alpha_n(J_{E_1}^p(u) - J_{E_1}^p(x^*)) \rangle \\ &= V_p(\alpha_n J_{E_1}^p(z_0) + (1 - \alpha_n)J_{E_1}^p(z_n), x^*) + \alpha_n \langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n+1} - z_0 \rangle \\ &= \Delta_p(J_{E_1}^q(\alpha_n + (1 - \alpha_n)J_{E_1}^p(z_n)), x^*) + \alpha_n \langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n+1} - x^* \rangle \\ &\leq \alpha_n \Delta_p(x^*, x^*) + (1 - \alpha_n)\Delta_p(z_n, x^*) + \alpha_n \langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n+1} - x^* \rangle \\ &\leq [1 - \alpha_n(1 - \zeta)]\Delta_p(x_n, x^*) + \alpha_n(1 - \zeta) \left[(1 - \zeta)^{-1} \left(\langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n+1} - x^* \rangle + \frac{\mu_n}{\alpha_n} \right) \right]. \end{aligned}$$

Claim 2. $\{\Delta_p(x_n, x^*)\}$ converges to zero. That is by Lemma 1.9 and Claim 3, we require only to show that $\limsup_{k \rightarrow \infty} \langle J_{E_1}^p(u) - J_{E_1}^p(x^*), x_{n_k+1} - x^* \rangle \leq 0$ for every subsequence $\{\Delta_p(x_{n_k}, x^*)\}$ of $\{\Delta_p(x_n, x^*)\}$ satisfying

$$\liminf_{k \rightarrow \infty} (\Delta_p(x_{n_k+1}, x^*) - \Delta_p(x_{n_k}, x^*)) \geq 0.$$

Now, suppose that $\{\Delta_p(x_{n_k}, x^*)\}$ is a subsequence of $\{\Delta_p(x_n, x^*)\}$ such that $\liminf_{k \rightarrow \infty} (\Delta_p(x_{n_k+1}, x^*) - \Delta_p(x_{n_k}, x^*)) \geq 0$. Then from (1.52), we get

$$\begin{aligned} \limsup_{k \rightarrow \infty} \Psi_{n_k} &\leq \liminf_{k \rightarrow \infty} [\Delta_p(x_{n_k}, x^*) - \Delta_p(x_{n_k+1}, x^*) + \alpha_{n_k} M_1] \\ &\leq \limsup_{k \rightarrow \infty} [\Delta_p(x_{n_k}, x^*) - \Delta_p(x_{n_k+1}, x^*)] + \limsup_{k \rightarrow \infty} \alpha_{n_k} M_1 \\ &\leq -\liminf_{k \rightarrow \infty} [\Delta_p(x_{n_k+1}, x^*) - \Delta_p(x_{n_k}, x^*)] + \limsup_{k \rightarrow \infty} \alpha_{n_k} M_1 \\ &\leq 0. \end{aligned}$$

This implies that

$$\lim_{k \rightarrow \infty} \Psi_{n_k} = 0,$$

where $\Psi_{n_k} := (1 - \alpha_n \zeta)\Delta_p(x_{n_k}, y_{n_k}) + (1 - C_q q^{-1}) \|J_{E_1}^p y_n - J_{E_1}^p v_n\|^q + \frac{\varepsilon^2 C_q}{q} \|B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}))\|^q$. Hence

$$(1.54) \quad \lim_{k \rightarrow \infty} \Delta_p(x_{n_k}, y_{n_k}) = \lim_{k \rightarrow \infty} \|J_{E_1}^p y_n - J_{E_1}^p v_n\| = \lim_{k \rightarrow \infty} \|B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}))\| = 0.$$

Thus, we obtain from (1.54) that

$$(1.55) \quad \lim_{k \rightarrow \infty} \|x_{n_k} - y_{n_k}\| = \lim_{k \rightarrow \infty} \|y_{n_k} - v_{n_k}\| = 0,$$

which implies that

$$(1.56) \quad \lim_{k \rightarrow \infty} \|x_{n_k} - v_{n_k}\| = 0.$$

Since S is ξ -demigeneralized mapping, by (1.23) and for some $M_2 > 0$, we get

$$\begin{aligned}
 \|B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}))\|M_2 &\geq \|B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}))\| \|v_{n_k} - x^*\| \\
 &\geq \langle B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k})), v_{n_k} - x^* \rangle \\
 &= \langle J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}), Bv_{n_k} - Bx^* \rangle \\
 &\geq \frac{1}{\xi} \Delta_p(Bv_{n_k}, SBv_{n_k}) \\
 &\geq \frac{\pi_p}{\xi} \|Bv_{n_k} - SBv_{n_k}\|^p,
 \end{aligned}$$

it follows from (1.54) that

$$(1.57) \quad \lim_{k \rightarrow \infty} \|Bv_{n_k} - SBv_{n_k}\| = 0.$$

By the definition of (z_n) and (1.54), we get

$$\begin{aligned}
 0 &\leq \|J_{E_1}^p z_{n_k} - J_{E_1}^p v_{n_k}\| \\
 &\leq \lambda_{n_k} \|B^*(J_{E_2}^p(Bv_{n_k}) - J_{E_2}^p(SBv_{n_k}))\| \rightarrow 0
 \end{aligned}$$

as $k \rightarrow \infty$, relying on the fact that $J_{E_1}^q$ is norm-to-norm uniformly continuous on bounded subset of E_1^* , we obtain

$$(1.58) \quad \lim_{k \rightarrow \infty} \|z_{n_k} - v_{n_k}\| = 0.$$

Combining (1.56) and (1.58), we get

$$(1.59) \quad \lim_{k \rightarrow \infty} \|z_{n_k} - x_{n_k}\| = 0.$$

Using (1.50), we get

$$\begin{aligned}
 \Delta_p(z_n, x^*) - \Delta_p(Tz_n, x^*) &= \Delta_p(z_n, x^*) - \Delta_p(x_{n+1}, x^*) + \Delta_p(x_{n+1}, x^*) - \Delta_p(Tz_n, x^*) \\
 &\leq \Delta_p(z_n, x^*) - \Delta_p(x_{n+1}, x^*) + \alpha_n \Delta_p(u, x^*) \\
 &\quad + (1 - \alpha_n) \Delta_p(Tz_n, x^*) - \Delta_p(Tz_n, x^*) \\
 &\leq (1 + \alpha_n \zeta) \Delta_p(x_n, x^*) + \alpha_n M - \Delta_p(x_{n+1}, x^*) - \alpha_n \Delta_p(Tz_n, x^*) \\
 &= [\Delta_p(x_n, x^*) - \Delta_p(x_{n+1}, x^*) + \alpha_n [\zeta \Delta_p(x_n, x^*) + M - \Delta_p(Tz_n, x^*)]]
 \end{aligned}$$

it follows that

$$\begin{aligned}
 \limsup_{k \rightarrow \infty} [\Delta_p(z_{n_k}, x^*) - \Delta_p(Tz_{n_k}, x^*)] &\leq \limsup_{k \rightarrow \infty} [\Delta_p(x_{n_k}, x^*) - \Delta_p(x_{n_k+1}, x^*)] \\
 &\quad + \limsup_{k \rightarrow \infty} \alpha_{n_k} [\zeta \Delta_p(x_{n_k}, x^*) + M - \Delta_p(Tz_{n_k}, x^*)] \\
 &\leq -\liminf_{k \rightarrow \infty} [\Delta_p(x_{n_k+1}, x^*) - \Delta_p(x_{n_k}, x^*)] \\
 &\leq 0
 \end{aligned}$$

hence

$$(1.60) \quad \lim_{k \rightarrow \infty} [\Delta_p(z_{n_k}, x^*) - \Delta_p(Tz_{n_k}, x^*)] = 0.$$

Thus, by the definition of T , we obtain

$$(1.61) \quad \lim_{k \rightarrow \infty} \Delta_p(Tz_{n_k}, z_{n_k}) = 0.$$

Therefore

$$(1.62) \quad \lim_{k \rightarrow \infty} \|Tz_{n_k} - z_{n_k}\| = 0.$$

Indeed, from (1.33) and (1.61), we get

$$\Delta_p(x_{n_k+1}, z_{n_k}) \leq \alpha_{n_k} \Delta_p(u, z_{n_k}) + (1 - \alpha_{n_k}) \Delta_p(Tz_{n_k}, z_{n_k}) \rightarrow 0,$$

as $k \rightarrow \infty$, hence

$$(1.63) \quad \lim_{k \rightarrow \infty} \|x_{n_k+1} - z_{n_k}\| = 0.$$

Combining (1.59) and (1.64), we get

$$(1.64) \quad \lim_{k \rightarrow \infty} \|x_{n_k+1} - x_{n_k}\| = 0.$$

Furthermore, from (1.31), we get

$$(1.65) \quad \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q = \frac{\rho_n^{q-1} \|J_{E_1}^p d_n\|^q}{K^*} = \frac{\|\rho_n J_{E_1}^p d_n\|^q}{K \rho_n} = \frac{\|J_{E_1}^p v_n - J_{E_1}^p y_n\|^q}{K^* \rho_n}$$

And by (1.35), we get

$$(1.66) \quad \frac{\|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q}{\|J_{E_1}^p d_n\|^q} \geq \frac{1}{2 \left(1 + C_q \left(\frac{\tau L}{K}\right)^q\right)}.$$

Therefore, we get

$$\rho_n^{q-1} = K^* \frac{\|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q}{\|J_{E_1}^p d_n\|^q} \geq \frac{K^*}{2 \left(1 + C_q \left(\frac{\tau L}{K}\right)^q\right)}$$

thus

$$(1.67) \quad \frac{1}{\rho_n} \leq \left(\frac{2 \left(1 + C_q \left(\frac{\tau L}{K}\right)^q\right)}{K^*} \right)^{\frac{1}{q-1}} =: \kappa$$

Combining (1.65) and (1.67), we obtain

$$(1.68) \quad \|J_{E_1}^p y_n - J_{E_1}^p w_n\|^q \leq \frac{\kappa}{K^*} \|J_{E_1}^p v_n - J_{E_1}^p y_n\|^q$$

Hence, from (1.54) and (1.68), we get

$$\|J_{E_1}^p y_{n_k} - J_{E_1}^p w_{n_k}\|^q \leq \frac{\kappa}{K^*} \|J_{E_1}^p v_{n_k} - J_{E_1}^p y_{n_k}\|^q \rightarrow 0$$

as $k \rightarrow \infty$. That is,

$$\lim_{k \rightarrow \infty} \|J_{E_1}^p y_{n_k} - J_{E_1}^p w_{n_k}\| = 0$$

and by property of $J_{E_1}^p$, we get

$$(1.69) \quad \lim_{k \rightarrow \infty} \|y_{n_k} - w_{n_k}\| = 0.$$

Since $\{x_{n_k}\}$ is bounded, there exists a subsequence say $\{x_{n_{k_j}}\}$ of $\{x_{n_k}\}$ that converges weakly to say $z \in E_1$ as $j \rightarrow \infty$. Then, from (1.55), we have that $\{y_{n_{k_j}}\}$ converges weakly to z as $j \rightarrow \infty$, so by (1.69) and Claim 1, we obtain that $z \in VI(C, A)$.

Next, we show that $Bz \in F(S)$. From (1.55), we get that $\{v_{n_{k_j}}\}$ converges weakly to z as $j \rightarrow \infty$ and since B is a bounded linear operator, then $\{Bv_{n_{k_j}}\}$ converges weakly to $Bz \in E_2$. Thus, combining (1.57) and demiclosedness of S , we obtain that $Bz \in F(S)$. Also, from (1.59), we get $z_{n_{k_j}}$ converges weakly to z , it follows from (1.62) that $z \in F(T)$,

since $F(T) = \hat{F}(T)$. Hence, from Claim 2, we get $z \in \Gamma := VI(C, A) \cap F(T) \cap B^{-1}(F(T))$. Since $x^* = \Pi_\Gamma u$, from (1.19), we get

$$\begin{aligned} \limsup_{k \rightarrow \infty} \langle J_{E_1}^p(u) - J_{E_1}^p x^*, x_{n_k} - x^* \rangle &= \lim_{j \rightarrow \infty} \langle J_{E_1}^p(u) - J_{E_1}^p x^*, x_{n_{k_j}} - x^* \rangle \\ (1.70) \qquad \qquad \qquad &= \langle J_{E_1}^p(u) - J_{E_1}^p x^*, z - x^* \rangle \leq 0. \end{aligned}$$

Combining (1.64) and (1.70), we get

$$\begin{aligned} \limsup_{k \rightarrow \infty} \langle J_{E_1}^p(u) - J_{E_1}^p x^*, x_{n_{k+1}} - x^* \rangle &= \limsup_{k \rightarrow \infty} \langle J_{E_1}^p(u) - J_{E_1}^p x^*, x_{n_k} - x^* \rangle \\ (1.71) \qquad \qquad \qquad &= \langle J_{E_1}^p(u) - J_{E_1}^p x^*, z - x^* \rangle \leq 0. \end{aligned}$$

Therefore, using Lemma 1.9 and Claim 3, we obtain that $\Delta_p(x_n, x^*) \rightarrow 0$ as $n \rightarrow \infty$, by (1.23), we know that $\pi_p \|x_n - x^*\|^p \leq \Delta_p(x_n, x^*) \rightarrow 0$. Hence, $x_n \rightarrow x^*$, where $x^* = \Pi_\Gamma u$. \square

2. NUMERICAL ILLUSTRATION

In this section, we provide some numerical examples for implementing our algorithm.

Example 2.1. We consider this example in $(\mathbb{R}^3, \|\cdot\|_2)$ of the problem considered in Theorem 1.3. For this example, let $C := \{x = (x_1, x_2, x_3) \in \mathbb{R}^3 : \langle a, x \rangle = b\}$, where $a = (2, -1, 5)$ and $b = 1$ then

$$\Pi_C(x) = P_C(x) = \frac{b - \langle a, x \rangle}{\|a\|_2^2}.$$

We choose the operators as follows: Let $T = P_C$, then T is a Bregman strongly nonexpansive mapping (see [31, 32]). We also define the ξ -Bregman demigeneralized type mapping $S : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ by $S(x) = \frac{1}{2}x + 1$ for all $x \in \mathbb{R}^3$. Let the mapping $A : C \rightarrow E_1^*$ be given by $A(x) = \frac{x}{2}$. Also, we define the bounded linear operator B by

$$B = \begin{pmatrix} 3 & -3 & -5 \\ -4 & 2 & -4 \\ -5 & -2 & 3 \end{pmatrix},$$

then

$$B^* = \begin{pmatrix} 3 & -4 & -5 \\ -3 & 2 & -2 \\ -5 & -4 & 3 \end{pmatrix}.$$

For this example, choose $\alpha_n = \frac{1}{150n+1}$, $\mu_n = \frac{1}{n^{1.1}}$, $\theta = \frac{1}{2}$, $\tau = \frac{1}{5}$ and $\lambda = 0.001$. We make different choices of the initial points x_0 and x_1 with $u = 0.1$ and a stopping criterion $\|x_{n+1} - x_n\| < 10^{-3}$.

Case 1: $x_0 = (1.01, 1.23, 0.01)$ and $x_1 = (1.19, -0.96, 1.01)$;

Case 2: $x_0 = (1, 1, 1)$ and $x_1 = (3, 0, 4)$;

Case 3: $x_0 = (-1, 1, -1)$ and $x_1 = (3.1, 0.78, 1)$;

Case 4: $x_0 = (0, 0.75, 0.25)$ and $x_1 = (0, 2, 0.2)$.

The report of this example is displayed in Figure 1.

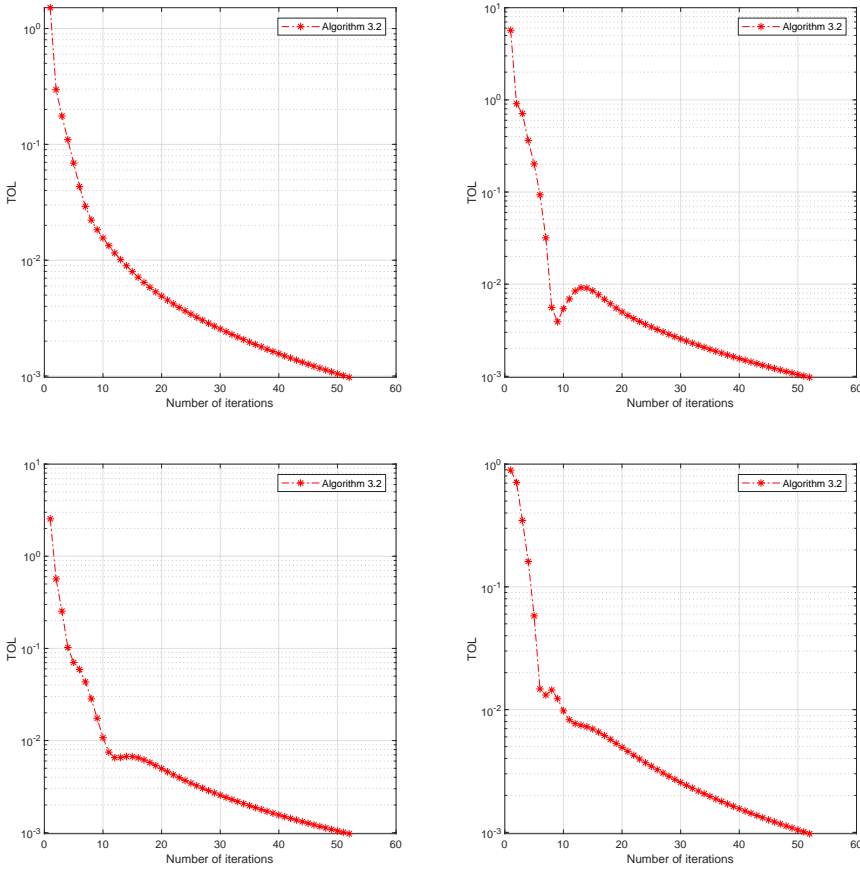


FIGURE 1. Example 2.1, Top left: Case 1; Top right: Case 2; Bottom left : Case 3; Bottom right: Case 4.

Example 2.2. Let $E_1 = E_2 = L_2([0, 1])$ with the inner product and norm given by $\langle x, y \rangle = \int_0^1 x(t)y(t)dt$ and $\|x\| = \int_0^1 |x(t)|^2 dt$, respectively. Let $C := \{x \in L_2([0, 1]) : \langle x, a \rangle = b\}$ where $a = 2t^2$ and $b = 1$. Then,

$$P_C(x) = \max \left\{ 0, \frac{b - \langle a, x \rangle}{\|a\|^2} \right\} a + x.$$

Let $A : C \rightarrow E_1^*$ be given by $A(x) = \max\{0, x(t)\}$ for all $x \in L_2([0, 1])$ and $t \in [0, 1]$. Define the bounded linear operator $B : E_1 \rightarrow E_2$ by $B(x) = \frac{x(t)}{2}$ and $T = P_C$. Also, let $S : E_2 \rightarrow E_2$ be defined by $S(y) = 2y(t)$ for all $y \in L_2([0, 1])$ and $t \in [0, 1]$.

For this example, choose $\alpha_n = \frac{1}{150n+1}$, $\mu_n = \frac{1}{3n+1.1}$, $\theta = \frac{1}{2}$, $\tau = \frac{1}{5}$ and $\lambda = 0.001$. We make different choices of the initial points x_0 and x_1 with $u = 0.1$ and a stopping criterion $\|x_{n+1} - x_n\| < 10^{-3}$.

Case I: $x_0 = t + 3$ and $x_1 = 2t$;

Case II: $x_0 = \sin(2t)$ and $x_1 = \cos(t)$;

Case III: $x_0 = e^{-t}$ and $x_1 = 2t^2$;

Case IV: $x_0 = \log(3t)$ and $x_1 = 11t + 1$.

The report of this example is displayed in Figure 2.

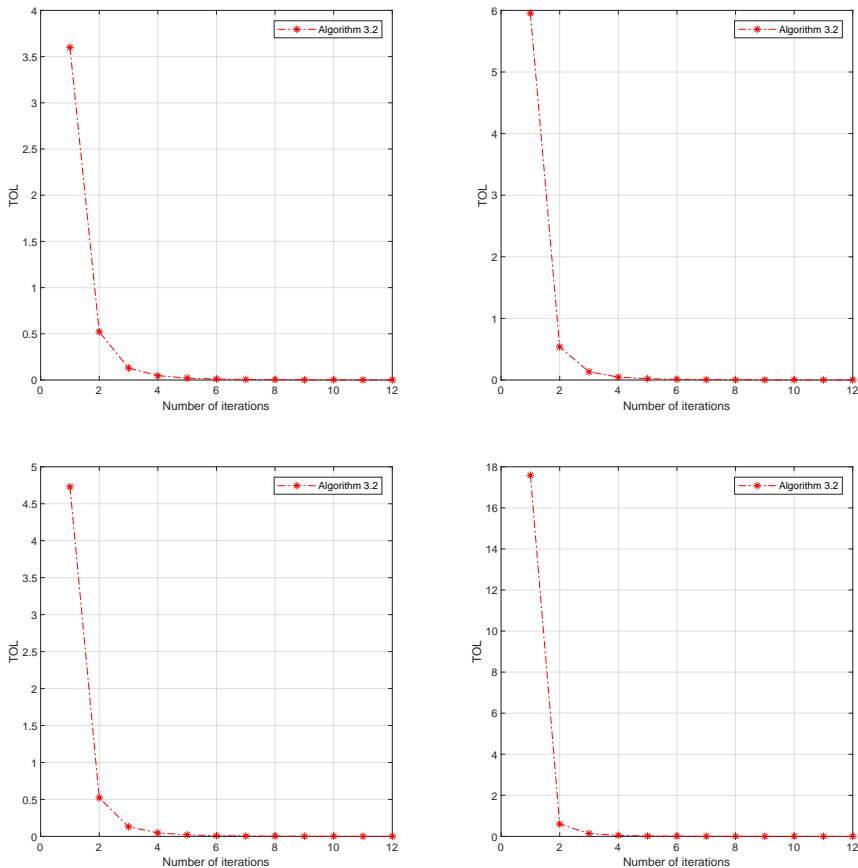


FIGURE 2. Example 2.2, Top left: Case I; Top right: Case II; Bottom left : Case III; Bottom right: Case IV.

3. CONCLUSIONS

We investigated a split variational inequality problem with a pseudomonotone operator and a fixed point issue in the context of real, uniformly convex, and uniformly real Banach spaces. To approximately solve the split variational inequality, a pseudomonotone problem, and the common fixed point of Bregman demigeneralized mapping and Bregman strongly nonexpansive mapping, we proposed a contraction and projection method, which is known to be one of the most effective methods for solving variational inequality. A method called inertial extrapolation was incorporated into our suggested algorithm to hasten the rate of convergence of our iterative approach which is new in Banach space. Strong convergence results were achieved by combining our algorithm with Halpern’s

method, and several numerical examples were used to demonstrate how well our method performed in comparison with some related ones.

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